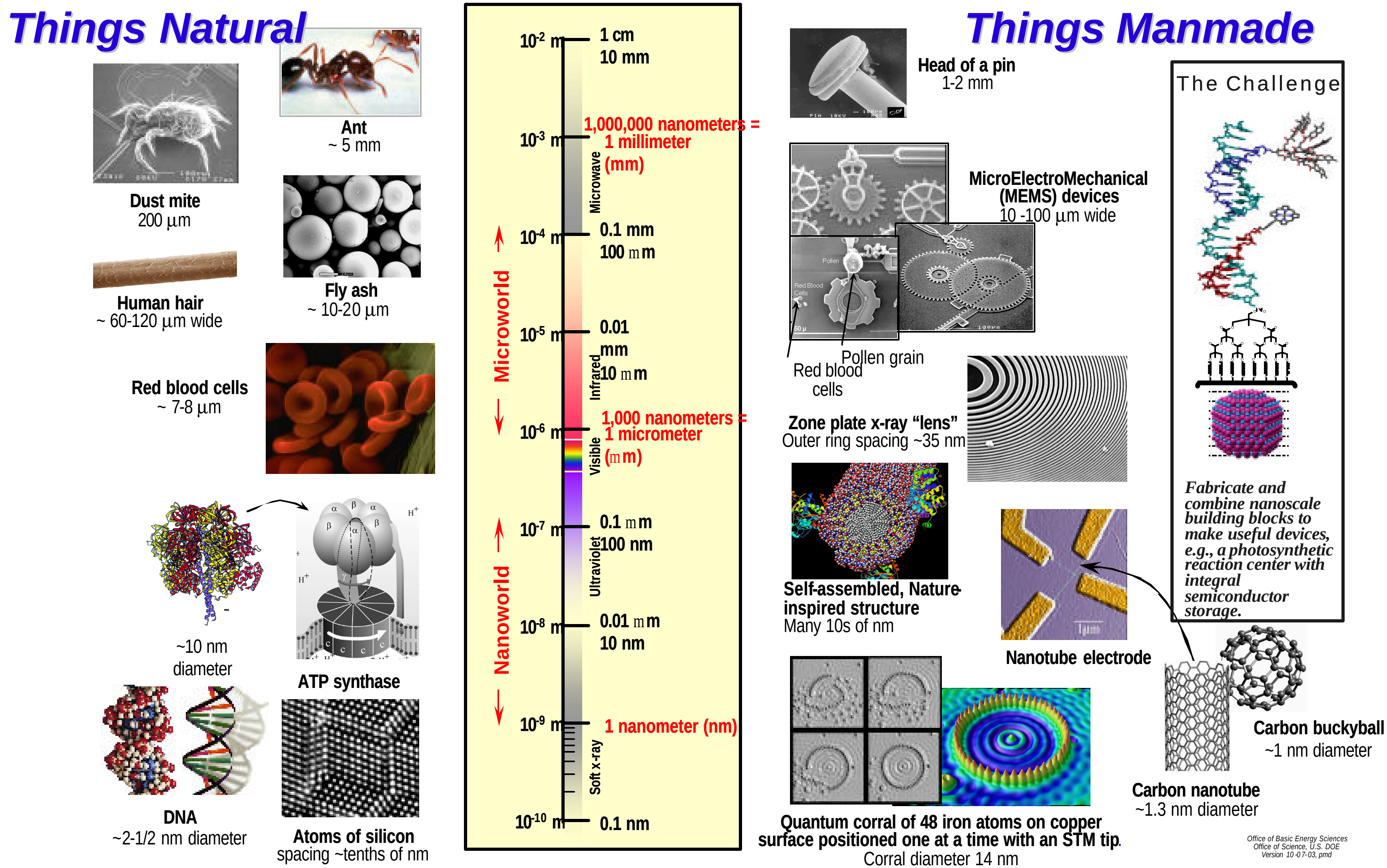
DOE Activities in Nanoscience and Nanotechnology

John C. Miller
Chemical Sciences, Geosciences and Biosciences Division
Office of Basic Energy Sciences

March 13, 2007

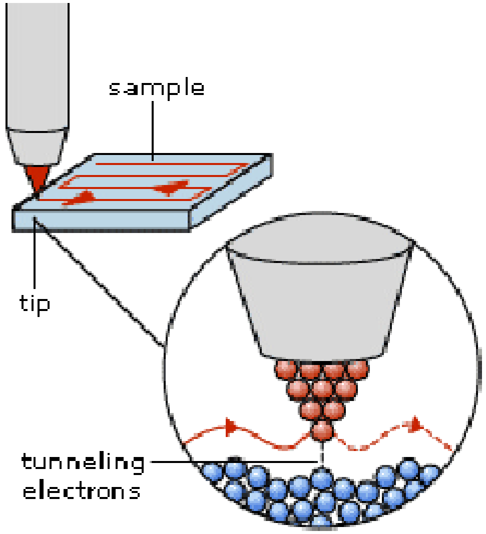
The Scale of Things – Nanometers and More

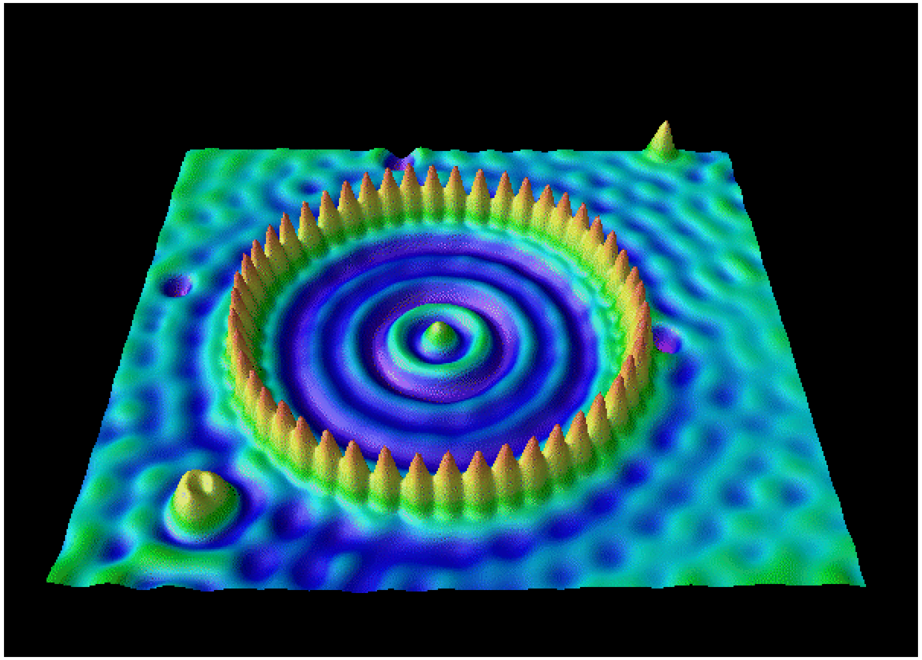


Tools to see and manipulate atoms

For example: the Scanning Tunneling Microscope (STM)
Invented by G. Binnig and H. Rohrer, IBM-Zurich in 1981
(awarded Nobel Prize in Physics, 1986)

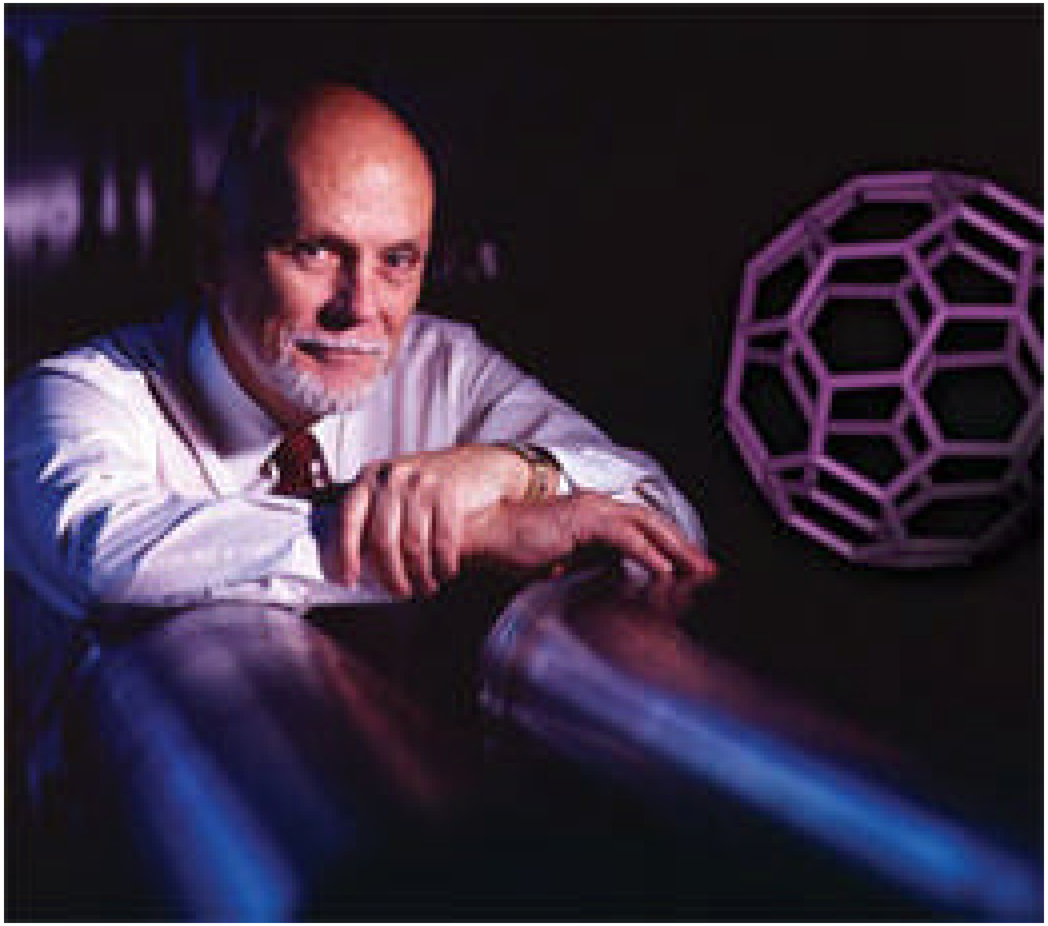
allowed direct observation of atoms on surfaces of metals



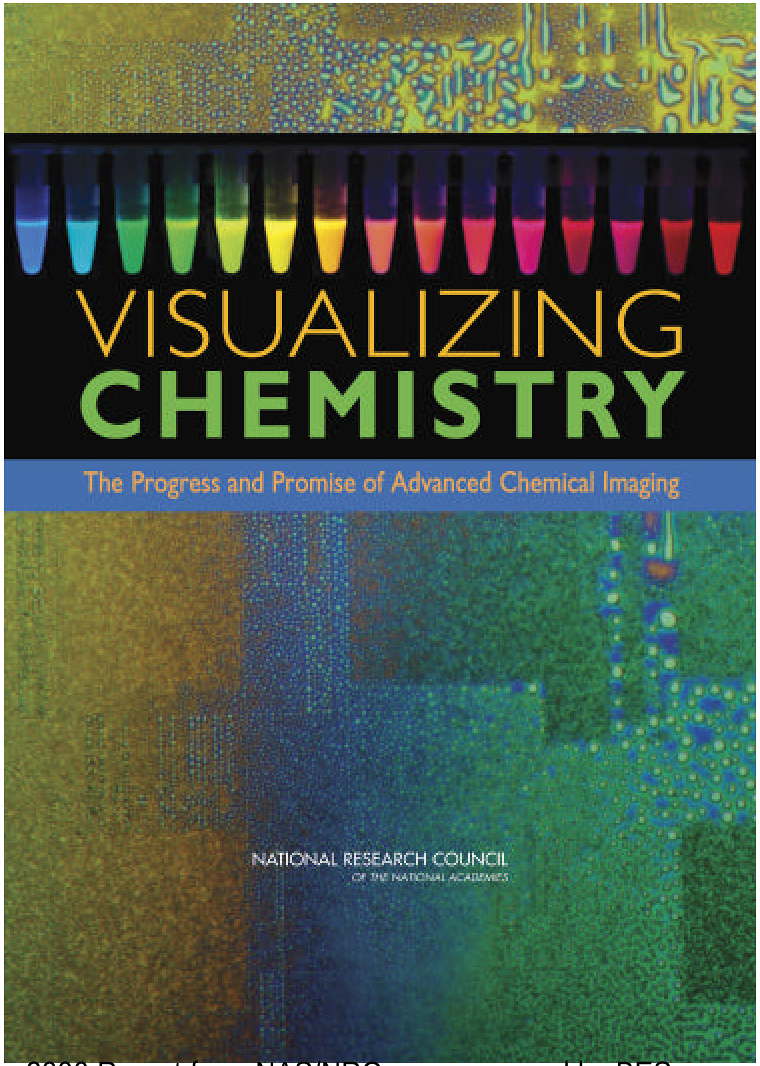


many advanced variants; can use to manipulate atoms ("quantum corral" of iron atoms on copper, D. Eigler and colleagues, IBM-Almaden)

Richard E. Smalley, 1943–2005



Visualizing Chemistry: The Promise of Advanced Chemical Imaging



2006 Report from NAS/NRC, co-sponsored by BES Chemical Sciences, Geosciences, and Biosciences Division

- **The emerging feasibility of "chemical imaging" is revolutionizing the way scientists can follow the chemical transformation of molecules on surfaces, within cells, or immersed in other complex environments.**
- **Chemical imaging is the term given to a set of experimental techniques that use photon or electron beams, or proximal electromechanical probes, to track molecules in two- or three-dimensional space and real time, while keeping track of their chemical identity and even their structure.**
- **In the ideal limit, chemical imaging means nanometer spatial resolution, femtosecond temporal resolution and "fingerprint" recognition of the molecular mass and structure.**
- **Recent examples include:**
  - Using focused laser beams (space and time information), coupled with mass spectrometry (chemical identification), to track specific metabolites in functioning cells. Multiplexing the mass information allows the simultaneous mapping of several species. Understanding the metabolic transformation of important biomolecules in cells is the first step toward influencing them in service of improved biochemical processes.
  - The use of chemical imaging to examine single-site catalysts as they influence reactions on surfaces and light-harvesting "antenna molecules" that are key participants in photochemical, charge-transfer processes.

Key Points

- *Nanoscale science and technology open up new realms of possibility for materials behavior and design, with consequences that relate directly to DOE missions*
- *DOE thus has critical interests in this area, and a major role in the corresponding federal research and development initiative*
  - *"… all of the elementary steps of energy conversion (e.g., charge transfer, molecular rearrangement, chemical reactions, etc.) take place on the nanoscale."*
  - *FY 2007: $258M at DOE (nearly $100M in construction and operation of scientific user facilities, and over $150M in basic research)*
- *DOE-supported research activities span a very broad range: nanotechnology is not a single "industry", but an enabling set of capabilities*
- *DOE user facilities, moving into full operations right now, provide state-of the-art resources to the entire science and technology community via peer-reviewed allocation of instrument time, staff support, and collaboration*

To begin with… Why does size matter?

What is “nanotechnology”?

- Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications…
- Nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale

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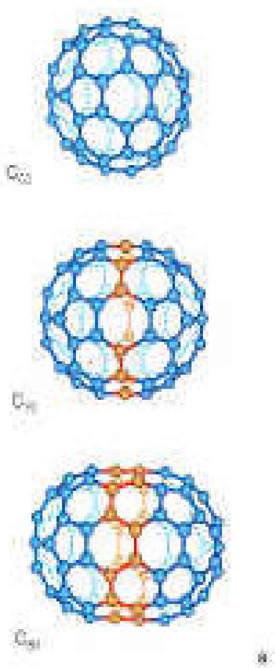
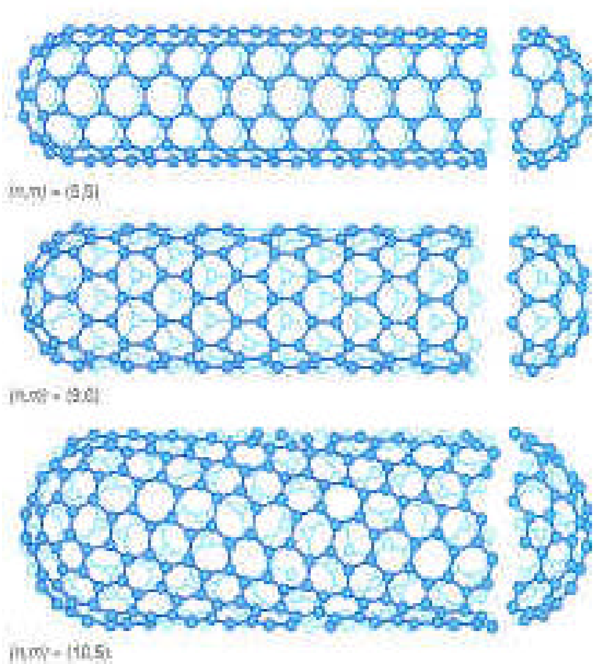
- Not just another step towards miniaturization; fundamental differences in physical, chemical, and biological behavior at this level compared to bulk materials or individual atoms/molecules
  - quantum phenomena
  - dominance of surfaces
  - self-assembly
  - etc.

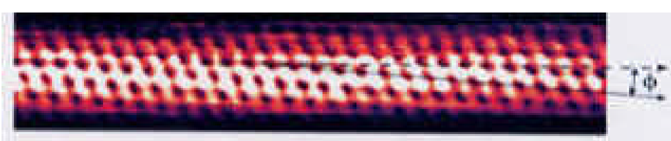
New forms of carbon at nanoscale dimensions

buckyballs



carbon nanotubes





Carbon atoms have long been known to combine in different structures to form two well-known materials:

> ***graphite (pencil lead)***
>
> ***diamond***

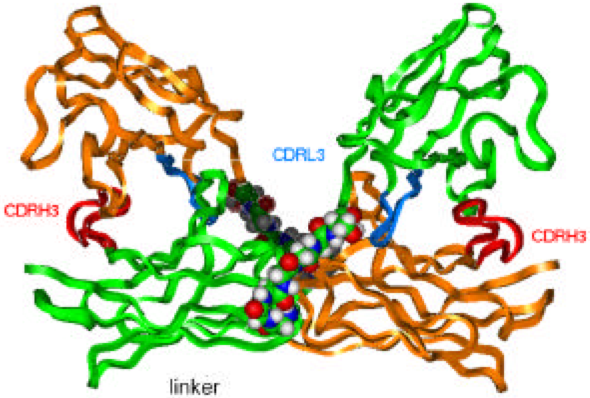
In addition, two new forms of carbon with limited dimensions on the nanometer scale were discovered in 1985 and 1991 respectively:

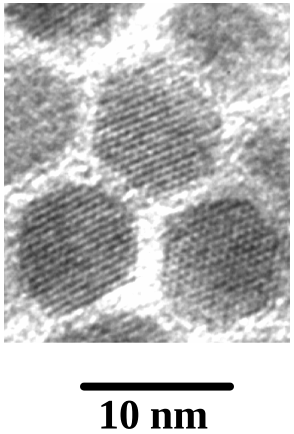
> ***buckminsterfullerenes (C_{60} et al.)***
>
> ***carbon nanotubes***

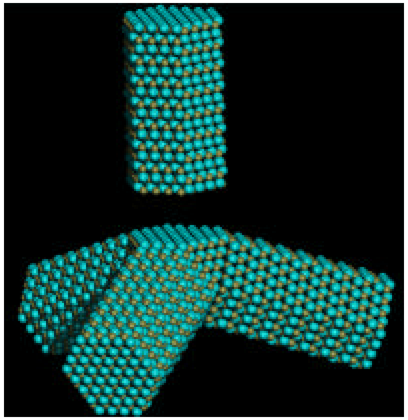
The nanotubes are rolled-up sheets of graphite, but the way they're arranged (armchair, zig-zag, helical) dramatically affects properties.

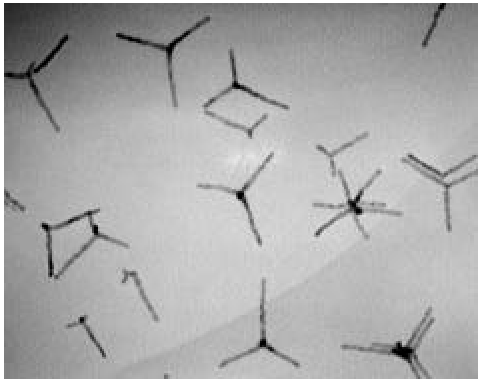
The diversity of nanoscale building blocks

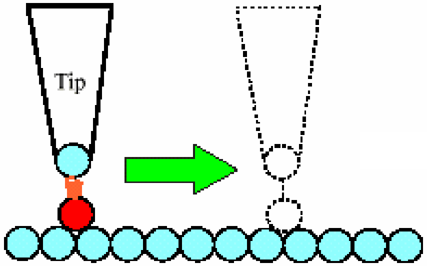
- ***nanocrystals***
- ***nanorods, nanotubes, nanowires***
- ***dendrimers***
- ***scanning probe tips***



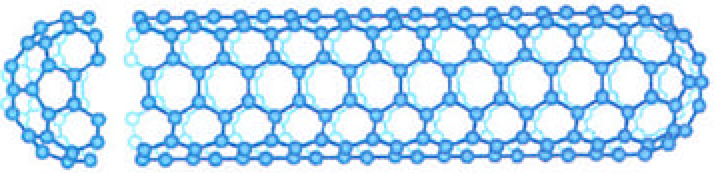


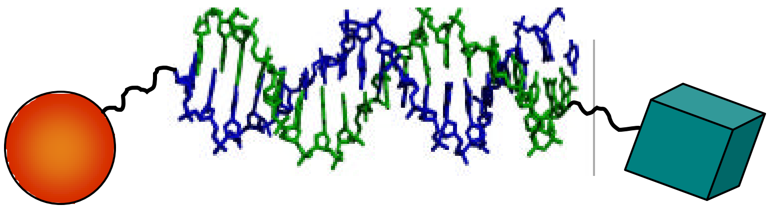


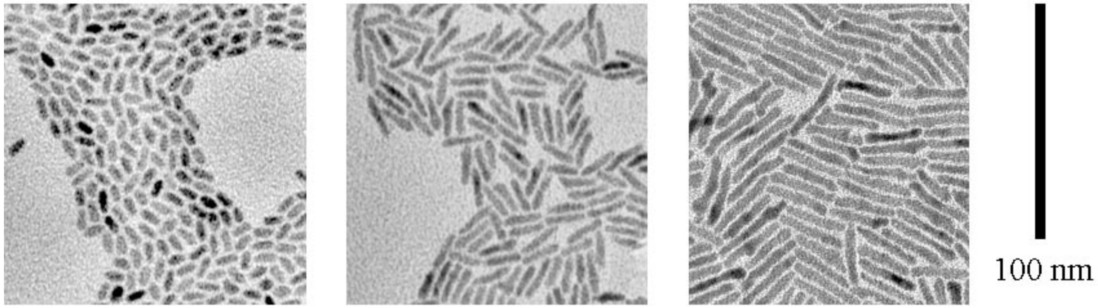




- ***patterned surface***
- ***cell membranes***
- ***DNA***
- ***proteins***

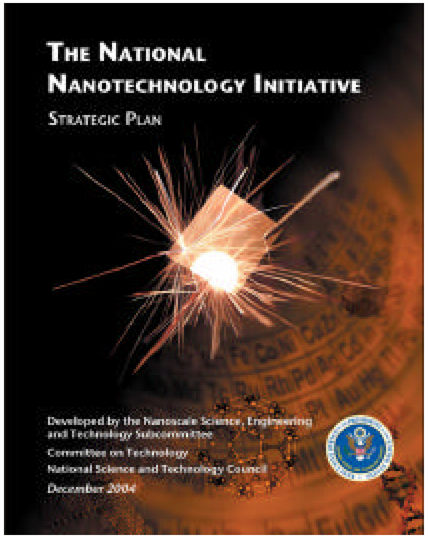




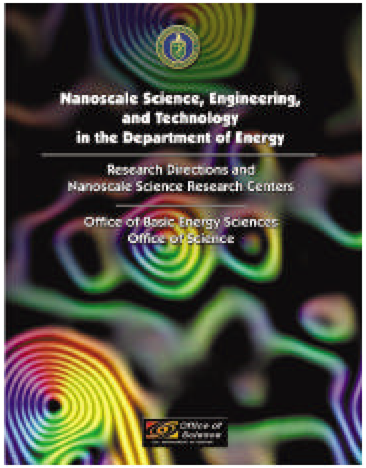


The National Nanotechnology Initiative, and DOE's role

NATIONAL NANOTECHNOLOGY INITIATIVE



- ***The National Nanotechnology Initiative (NNI) is an interagency program, started in 2001, that coordinates the Federal nanoscale research and development portfolio among 25 participating organizations***
- ***Planned federal NNI expenditures are over $1.2 billion in FY 2007***



- ***The Department of Energy is one of the original participants in the NNI, and provides major funding for nanoscale science, engineering, and technology. The FY 2007 budget request includes over $250 million for DOE nanoscience, which supports both fundamental research and facilities.***

21st Century Nanotechnology R&D Act, December 3, 2003

On December 3, 2003, President Bush signed the 21st Century Nanotechnology Research and Development Act, which authorizes funding for nanotechnology research and development over four years, starting in FY 2005.

Secretary of Energy Spencer Abraham, who was present at the White House Oval Office ceremony, applauded the signing of the act. "As one of the lead agencies for nanotechnology research and development, the Department of Energy (DOE) is delighted that the President signed legislation today that brings us closer to that future," … "This new science of very small things can revolutionize the way we produce, use, and deliver energy …."

President Bush is joined by, from left, Stephen Empedocles SVP of NanoSys, F. Mark Modezlewski, Exec. Director NanoBusiness Alliance, Rep. Sherwood Boehlert, R-NY. , Spencer Abraham , Dr. Richard Smalley, Nobel laureate from Rice University, Alliance Board Member Steve Jurvetson of Draper Fisher Jurvetson, Sen. George Allen , R-Va., Floyd Kvamme of the President's Council of Advisors on Science and Technology, Alliance Board Member James Von Ehr, founder and president of Zyvex, and Alliance Board Member Josh Wolfe of Lux Capital and Nanotech Report, Joe Piche, CEO of Eikos.

NNI activities and documents inform the federal activity, provide resources to the community, and report outcomes

Lots more information: see http://nano.gov

NNI budget in the FY 2007 request

- ***Federal NNI expenditures are currently estimated at roughly $1.3 billion/year. From OSTP documents accompanying the FY 2007 President's request:***

National Nanotechnology Initiative (dollars in millions)

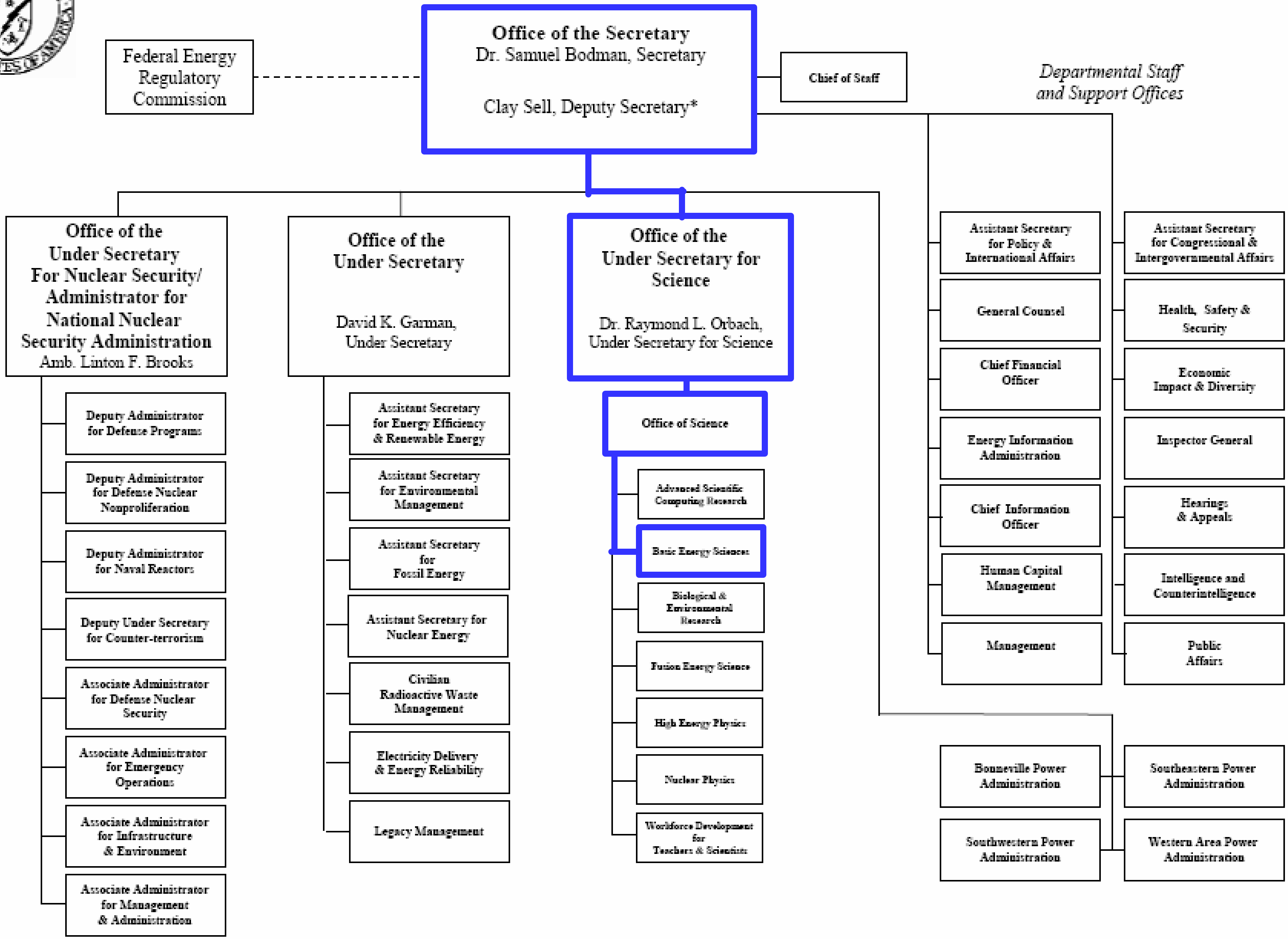
2006 request: 1,054

	2001 Actual	2006 Estimate	2007 Proposed	Dollar Change 2001 to 2007	% Change 2001 to 2007
National Science Foundation	150	344	373	223	149%
Defense	125	436	345	220	176%
Energy*	88	207	258	170	193%
Health & Human Services *	40	175	173	133	333%
Commerce (NIST)	33	76	86	53	161%
NASA	22	50	25	3	14%
EPA	5	5	9	4	80%
Agriculture *	0	5	5	5	N/A
Homeland Security	0	2	2	2	N/A
Justice	1	1	1	0	0.0%
TOTAL	**464**	**1,301†**	**1,277**	**813**	**175%**

* 2006 and 2007 funding levels for: DOE includes Basic Energy Sciences and Fossil Energy; HHS includes NIH and NIOSH funding; and USDA includes CSREES and Forest Service.

† 2006 estimate includes Congressional earmarks that are outside the NNI plan totaling over $100 million at DOD and over $10 million at NASA.

DEPARTMENT OF ENERGY



* The Deputy Secretary also serves as the Chief Operating Officer

26 Oct 06

DOE-SC-BES nanotechnology budget – FY 2007 Request

Nanoscale Science Research Funding

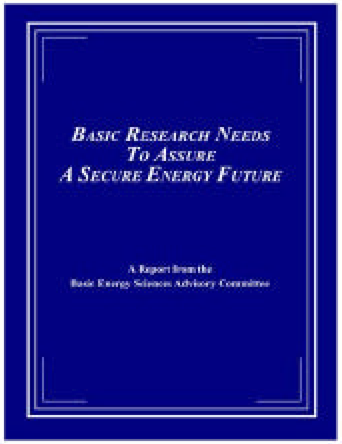
(dollars in thousands)

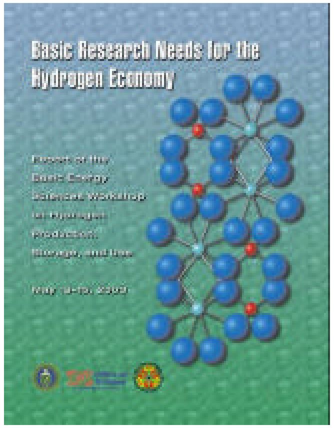
	TEC	TPC	FY 2005	FY 2006	FY 2007
Materials Sciences and Engineering					
Research			65,307	70,328	108,542
Major Item of Equipment, Center for Nanophase Materials (ANL)			12,000	14,000	—
Facility Operations					
Center for Functional Nanomaterials (BNL)			—	—	—
Center for Integrated Nanotechnologies (SNL/A & LANL)			—	11,900	19,190
ORNL, Center for Nanophase Materials Sciences			—	17,800	19,190
Center for Nanophase Materials (ANL)			—	3,500	19,190
Molecular Foundry (LBNL)			—	8,100	19,190
Chemical Sciences, Geosciences, and Biosciences					
Research			27,645	26,914	49,109
Project Engineering Design and Construction					
PED– All sites		21,318	1,996	—	—
Construction					
Center for Functional Nanomaterials (BNL)	79,700	81,000	18,317	36,187	18,864
Center for Integrated Nanotechnologies (SNL/A & LANL)	73,754	75,754	30,650	4,580	247
ORNL, Center for Nanophase Materials Sciences	63,740	64,740	17,669	—	—
Molecular Foundry (LBNL)	83,604	84,904	31,828	9,510	257
Total			205,412	202,819	253,779

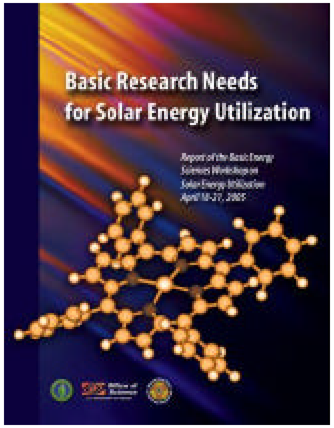
grants and lab research, via peer review

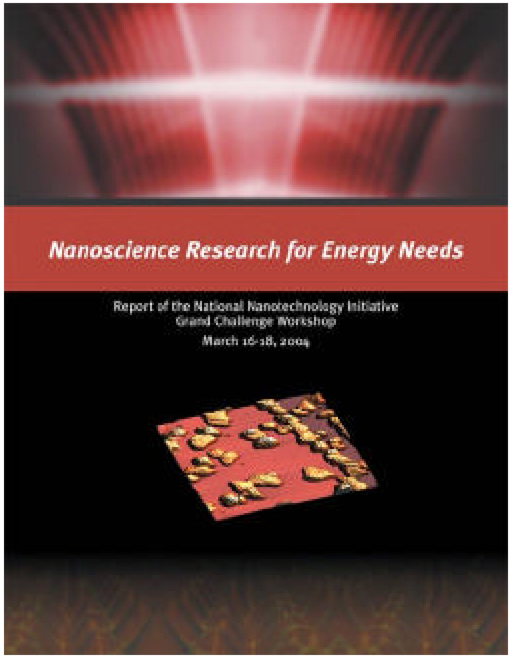
the rest is for scientific user facilities

Drivers for DOE support of nanoscience research









- ***Energy & environmental grand challenge areas identified from the start of the National Nanotechnology Initiative in FY 2001***
- ***DOE-SC-BES workshops cited nanoscience as a cross-cutting theme***:
  Basic Research Needs To Assure A Secure Energy Future (2002)
  Basic Research Needs for the Hydrogen Economy (2003)
  Basic Research Needs for Solar Energy Utilization (2005)
- ***Major NNI- and DOE-sponsored workshop in 2004 identified key research targets and foundational themes for energy-related nanoscience.***

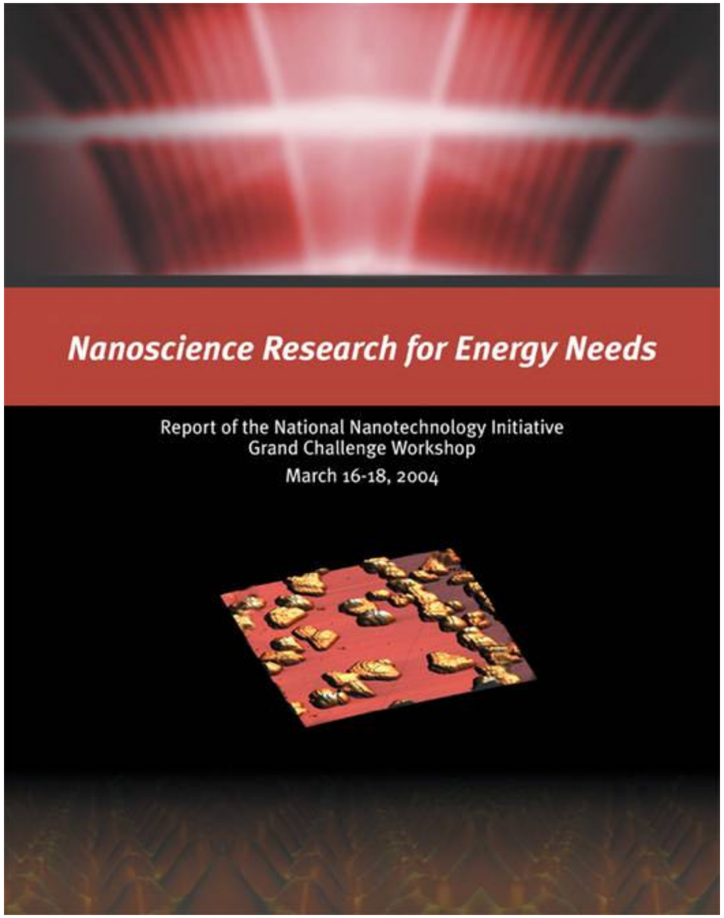
(All DOE-BES reports: see http://www.sc.doe.gov/bes/reports/list.html)

Strategic Planning, Part I: Basic Research in Support of the DOE Missions

To advance energy and national security

- **Basic Research Needs to Assure a Secure Energy Future**
  BESAC Workshop, October 21-25, 2002
  The foundation workshop that set the model for the focused workshops that follow.
- **Basic Research Needs for the Hydrogen Economy**
  BES Workshop, May 13-15, 2003
- **Nanoscience Research for Energy Needs**
  BES and the National Nanotechnology Initiative, March 16-18, 2004
- **Basic Research Needs for Solar Energy Utilization**
  BES Workshop, April 18-21, 2005
- **Advanced Computational Materials Science: Application to Fusion and Generation IV Fission Reactors**
  BES, ASCR, FES, and NE Workshop, March 31-April 2, 2004
- **The Path to Sustainable Nuclear Energy: Basic and Applied Research Opportunities for Advanced Fuel Cycles**
  BES, NP, and ASCR Workshop, September 2005
- **Basic Research Needs for Superconductivity**
  BES Workshop, May 8-10, 2006
- **Basic Research Needs for Solid-state Lighting**
  BES Workshop, May 22-24, 2006
- **Basic Research Needs for Advanced Nuclear Energy Systems**
  BES Workshop, July 31-August 3, 2006
- **Basic Research Needs for the Clean and Efficient Combustion of 21st Century Transportation Fuels**
  BES Workshop, October 30-November 1, 2006
- **Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems**
  BES Workshop, February 21-23, 2007
- **Basic Research Needs for Electrical Energy Storage**
  BES Workshop, April 2-5, 2007

Energy conversion happens at the nanoscale



Nanoscience Research for Energy Needs (2004)

- ***From the Executive Summary:***

  "At the root of the opportunities provided by nanoscience to enhance our energy security is the fact that all of the elementary steps of energy conversion (e.g., charge transfer, molecular rearrangement, chemical reactions, etc.) take place on the nanoscale."

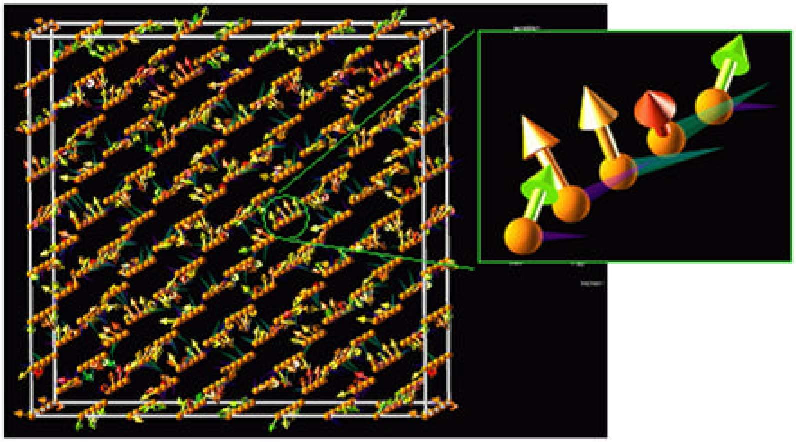
Nanotechnology Impact Areas in Energy & Environment

- **Energy**
  - *hydrogen storage*
  - *solid-state lighting*
  - *low-power displays*
  - *fuel cells*
  - *battery materials*
  - *solar power*
  - *catalysis*
  - *weight reduction*
  - *propellants and explosives*
  - *nanoscale energy (ATP motors, etc.)*

- **Environment**
  - *sensors*
  - *remediation*
  - *emissions reduction*
  - *membranes and separations*
  - *coatings*
  - *green processing*
  - *radioactive waste containment, etc.*

The mission of the Office of Basic Energy Sciences

- ***Foster and support <u>fundamental</u> research to provide the <u>basis</u> for new, improved, environmentally conscientious energy technologies***



- ***<u>Plan, construct, and operate major scientific user facilities</u> for "materials sciences and related disciplines" to serve researchers from academia, federal laboratories, and industry***

Office of Basic Energy Sciences

Patricia Dehmer, Director
Mary Jo Martin, Administrative Specialist

Director's Office Staff
Robert Astheimer
Linda Blevins
Richard Burrow
Margie Davis
F. Don Freeburn
Kensley Rivera
Karen Talamini

Materials Sciences and Engineering Division
Harriet Kung, Director
Christie Ashton, Program Analyst
Ann Lundy, Secretary

Materials and Engineering Physics
Harriet Kung, Acting
Vacant, Prog. Asst.

- **Structure & Composition of Materials**
  Jane Zhu
  ■ Peter Tortorelli, ORNL
- **Mechanical Behavior of Materials & Rad Effects**
  Yok Chen
  John Vetrano
  ■ Richard Wright, INL
- **Physical Behavior of Materials**
  Refik Kortan
  ■ Jeffrey Tsao, SNL
- **Synthesis & Processing Science**
  Timothy Fitzsimmons
  Bonnie Gersten
  ◆ Daniel Friedman, NREL
- **Engineering Research**
  Timothy Fitzsimmons

Condensed Matter Phys and Materials Chemistry X-Ray & Neutron Scat.
Helen Kerch
Vacant, Prog. Asst.

- **Experimental Condensed Matter Physics**
  James Horwitz
  ■ Gary Kellogg, SNL
  ■ Doug Finnemore, Ames
- **Theoretical Condensed Matter Physics**
  Dale Koelling
  ■ Randy Fishman, ORNL
- **Materials Chemistry & Biomolecular Materials**
  Dick Kelley
  Aravinda Kini
  ■ David Beach, ORNL
- **X-ray & Neutron Scattering**
  Helen Kerch
  ■ Helen Farrell, INL
- **Experimental Program to Stimulate Competitive Research (EPSCoR)**
  Kristin Bennett

Scientific User Facilities Division
Pedro Montano, Director
Linda Cerrone, Program Support Specialist

- **X-Ray, Neutron, & Electron Scattering Facilities**
  Roger Klaffky
  Altaf (Tof) Carim
- **Spallation Neutron Source (Construction)**
  Jeffrey Hoy
- **Nanoscale Science Research Centers (Construction)**
  Altaf (Tof) Carim
  ◆ Tom Brown, ANL
- **Linac Coherent Light Source (Construction)**
  Jeffrey Hoy
- **Instrument MIEs (SNS, LCLS, etc.)**
  Jeffrey Hoy
  ◆ Tom Brown, ANL
- **NSLS II**
  Vacant
  ◆ Tom Brown, ANL

Chemical Sciences, Geosciences, and Biosciences Division
Eric Rohlfing, Director
Diane Marceau, Program Analyst
Michaelene Kyler-King, Program Assistant

Fundamental Interactions
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Robin Felder, Prog. Asst.

- **Atomic, Molecular, and Optical Science**
  Michael Casassa
- **Chemical Physics**
  Gregory Fiechtner
  ▲ Frank Tully, SNL
- **Photochemistry & Radiation Research**
  Mary Gress
  ◆ Mark Spitler, NREL
- **Computational and Theoretical Chemistry**
  Richard Hilderbrandt

Molecular Processes and Geosciences
John C. Miller
Teresa Russ, Prog. Asst.

- **Catalysis and Chemical Transformation**
  Raul Miranda
  ◆ Michael Chen, ANL
- **Separations and Analysis**
  William Millman
  ◆ Larry Rahn, SNL
- **Heavy Element Chemistry**
  Lester Morss
  ■ Norman Edelstein, LBNL
- **Chemical Energy and Chemical Engineering**
  Paul Maupin
- **Geosciences Research**
  Nicholas Woodward
  ★ Marsha Bollinger, AAAS

Energy Biosciences Research
Richard Greene, Acting
Dennis Burmeister, Prog. Asst.

- **Plant Sciences Biochemistry and Biophysics**
  Richard Greene
  ■ Michael Kahn, PNNL
  ◆ Pin-Ching Maness, NREL

Legend
▲ IPA
◆ Detailee
■ Detailee, 1/4 time, not at HQ
★ AAAS Fellow, 1/2 time

October 2006

DOE nanoscience programs

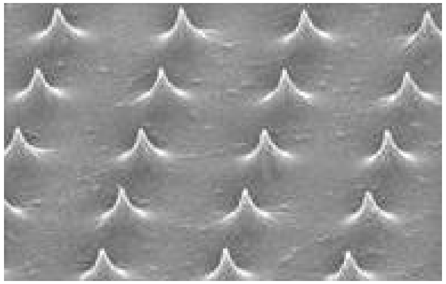
- **Core research programs in the Office of Science** (http://www.science.doe.gov/grants)
  - Annual Office of Science notices: continuing solicitations listing broad science areas and objectives
  - Primary criterion is quality of fundamental science; rigorous external peer review
- **Targeted solicitations** (http://www.science.doe.gov/grants)
  - e.g.: FY 2001, FY 2002 Nanoscale Science, Engineering, and Technology Notices
    - awarded ~$45M (>120 grants and 24 laboratory awards)
  - e.g.: FY 2003 solicitation on "Theory, Modeling and Simulation in Nanoscience":
    - awarded ~$4.3M for 4 projects involving 13 universities and 4 national laboratories
- **SBIR/STTR** (http://sbir.er.doe.gov/sbir)
  - Past solicitations have contained numerous relevant technical topics, including e.g.:
    - Nanotechnology for Coatings in Coal-Fired Environments
    - Nanotechnology Applications in Industrial Chemistry
- **Major research facilities** (http://www.sc.doe.gov/bes/BESfacilities.htm)
  - BES Nanoscale Science Research Centers – the DOE "flagship" NNI activity
  - BES supports synchrotron, neutron, and electron scattering (and other) user facilities

Nanostructured diamond for use in artificial retina

Ultrananocrystalline diamond (UNCD)

(Developed in a basic research program in Materials Sciences at ANL)

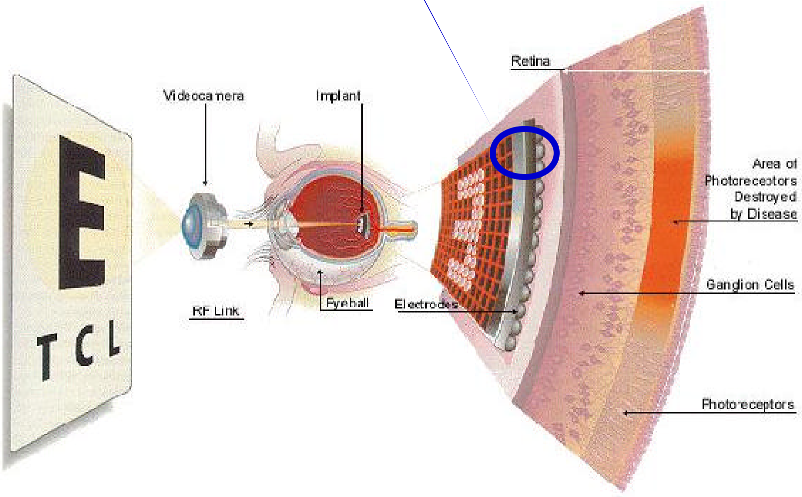
- ***Combination of excellent properties***
  - ***Mechanical***
  - ***Tribological***
  - ***Electrochemical***
  - ***Transport***
  - ***Biocompatible and Bioinert***



UNCD Electrode Array

Applications in Artificial Retina Chip

- ***Excellent hermetic coating material***
- ***Being evaluated as the electrode material***



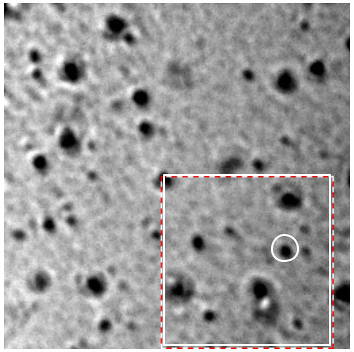
Project Participants:

5 DOE Labs (ANL, LANL, LLNL, ORNL, SNL),
2 Universities (USC, NCSU) and a Private Company (Second Sight)

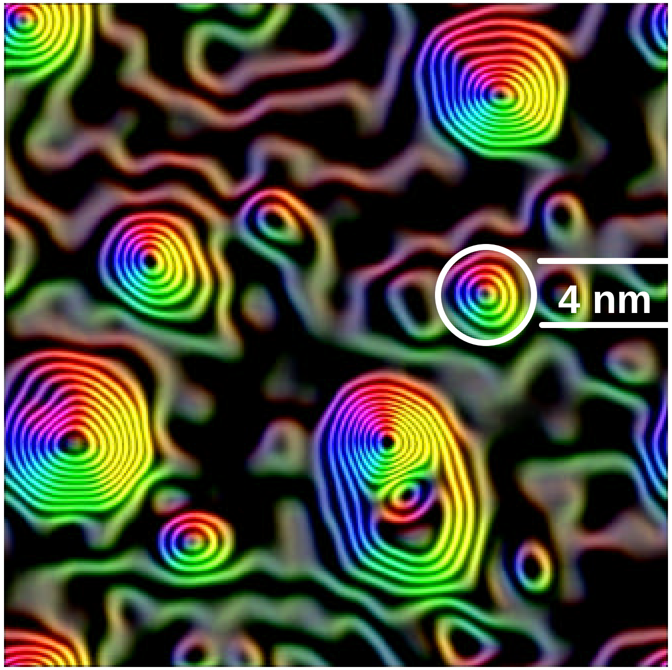
Nanoscale magnetic flux distribution

- ***Quantitative methods have been developed for imaging the distribution of magnetic flux at the nanometer scale***
- ***Approach is based on a novel solution of the equations governing intensity in defocused images***
- ***This technique is applied here to assess interdependence of neighboring magnetic (Ni) particles in a non-magnetic (SiO_2) matrix***

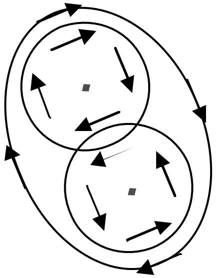
Experimental under-focused Fresnel image



Flux distribution map F (x,y)



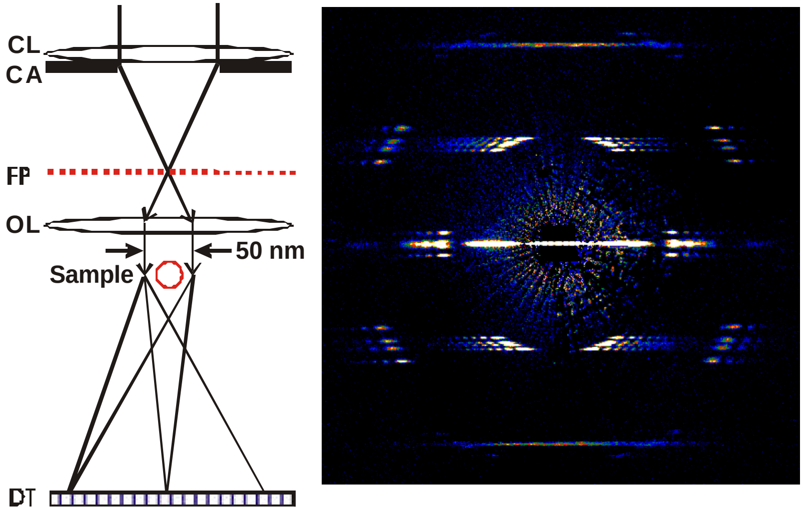
Magnetic coupling of Ni-nanoparticles



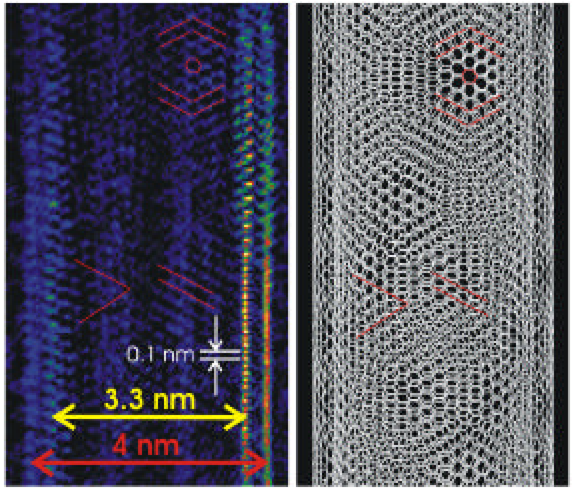
S. Volkov, Y. Zhu, et al., BNL

Imaging the structure of an individual double-walled carbon nanotube

An advanced new application of transmission electron microscopy uses data from coherent electron diffraction to construct atomic-scale structural images of single molecules.



(left) A single double wall nanotube is illuminated with a narrow beam of electrons.
(right) The diffraction pattern of the tube



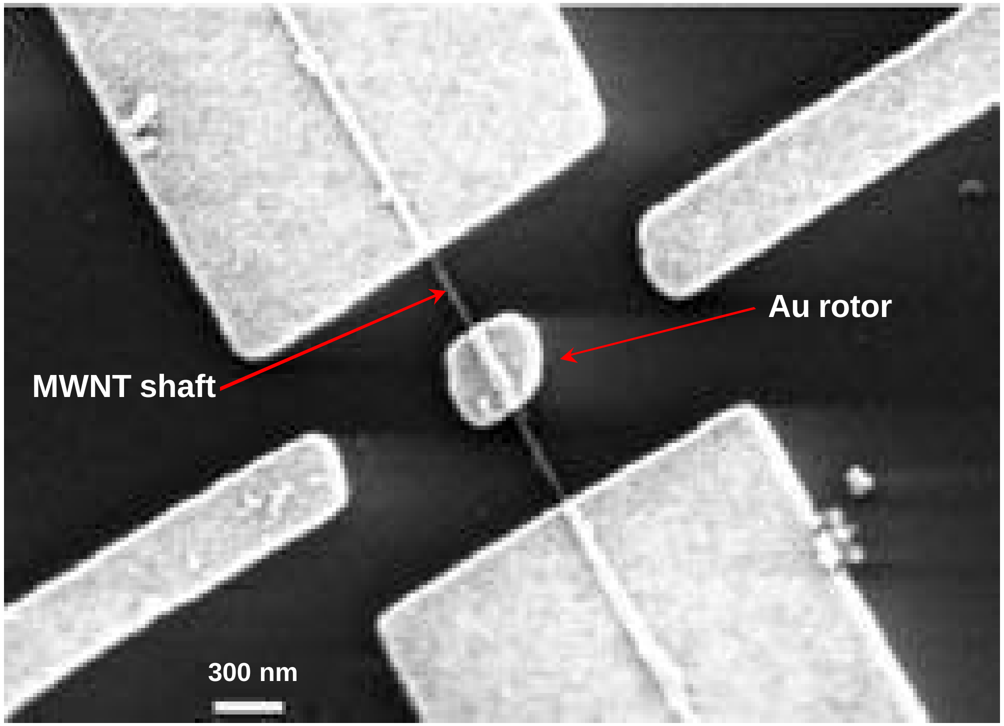
The reconstructed atomic resolution image of a double wall carbon nanotube and a structure model.
Science 300, 1419 (2003)

In a tour-de-force demonstration, the atomic-scale structures of both inner and outer tubes in an individual double-wall carbon nanotube have been determined.

J.M. Zuo, I. Vantanyants, M. Gao (UIUC); R. Zhang, L. Nagahara (Motorola)

First Synthetic Nanomotor

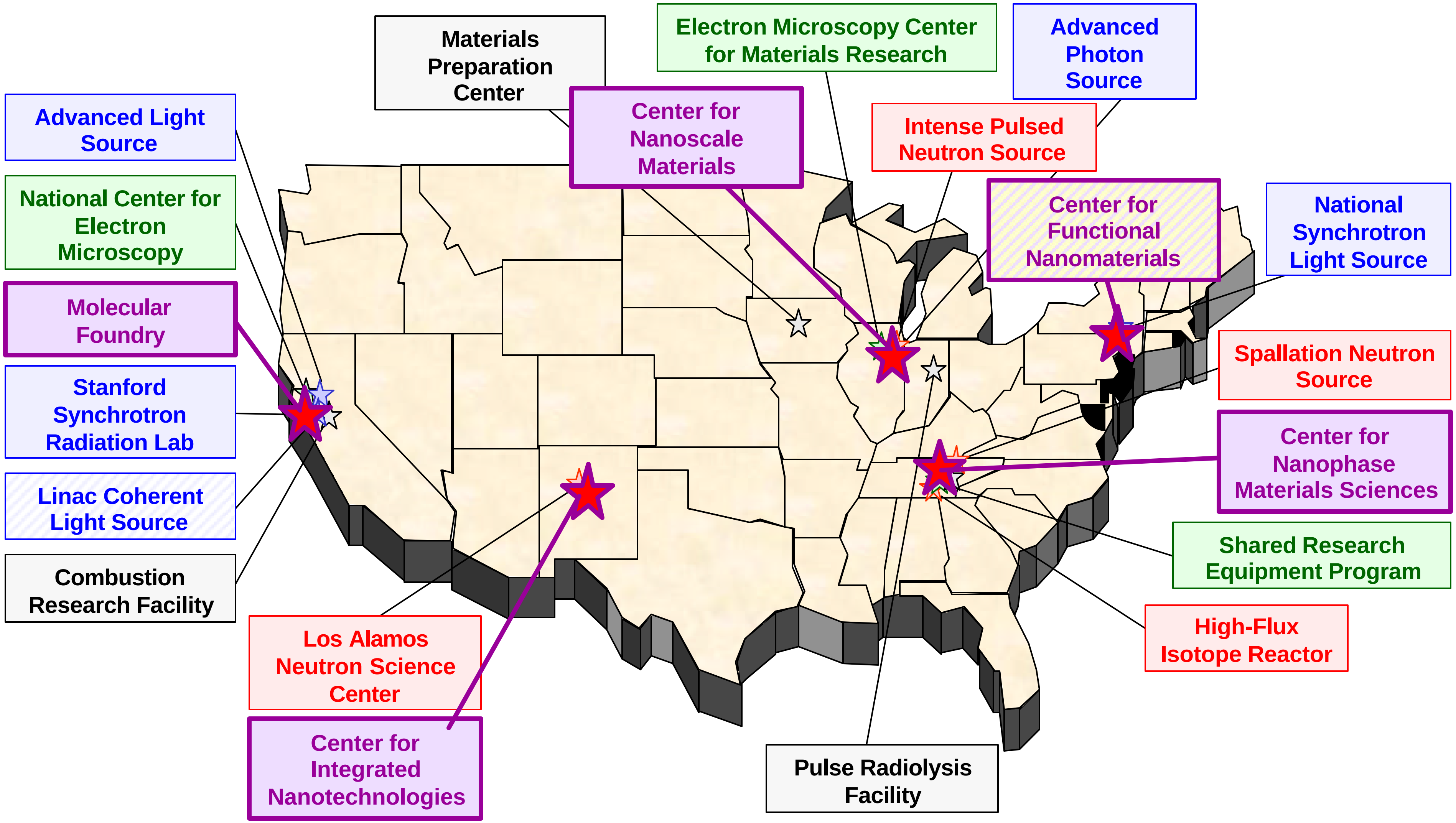
2004 R&D 100 Winner



A. Zettl et al., LBNL

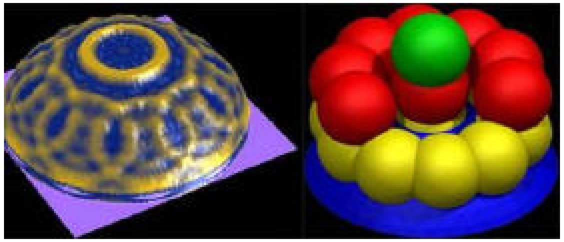
Scanning electron microscopy (SEM) image of LBNL's synthetic nanomotor. A 300 nm Au plate rotor is attached to a multi-walled carbon nanotube (MWNT) which acts as a support shaft and is the source of rotational freedom. The rotor can rotate through a full 360 degrees for thousands of cycles without apparent degradation or wear.

DOE-BES User Facilities, including the NSRCs (★)

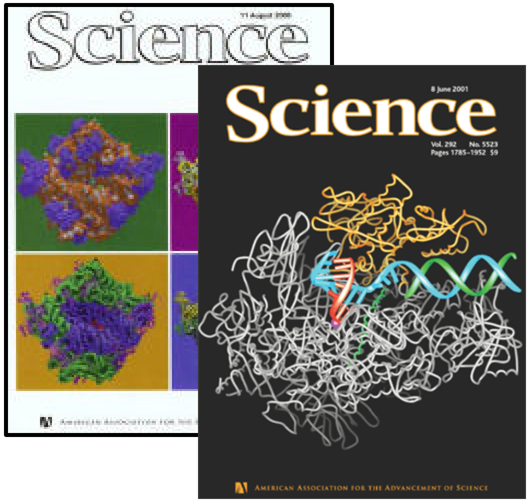


Seeing atoms:
Providing national user facilities for probing materials at the atomic scale

X-ray scattering

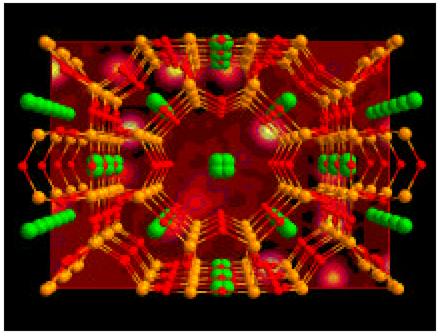


AlNiCo quasicrystal structure

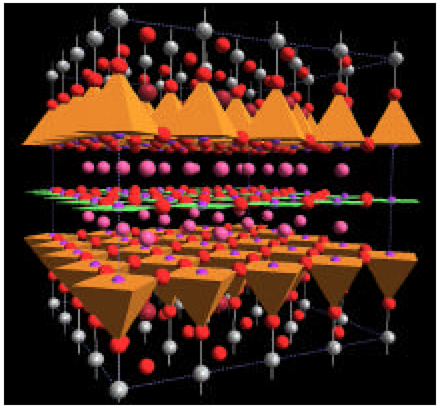


Molecular machines of life

Neutron scattering

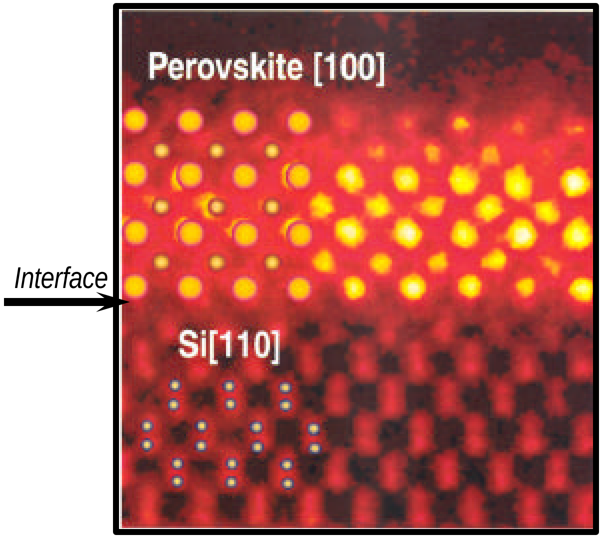


Zeolite catalyst



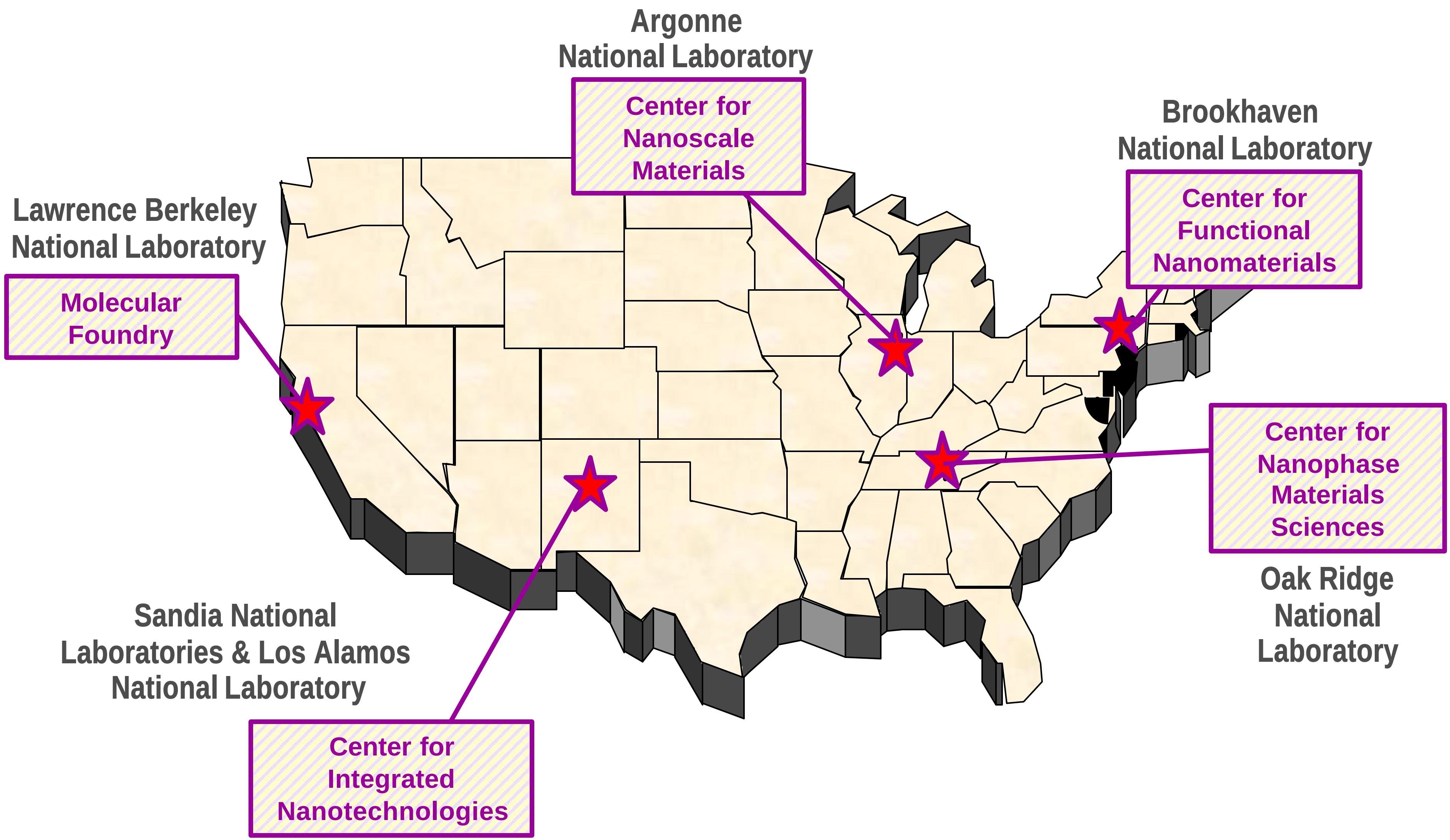
High Tc superconductor

Electron Scattering



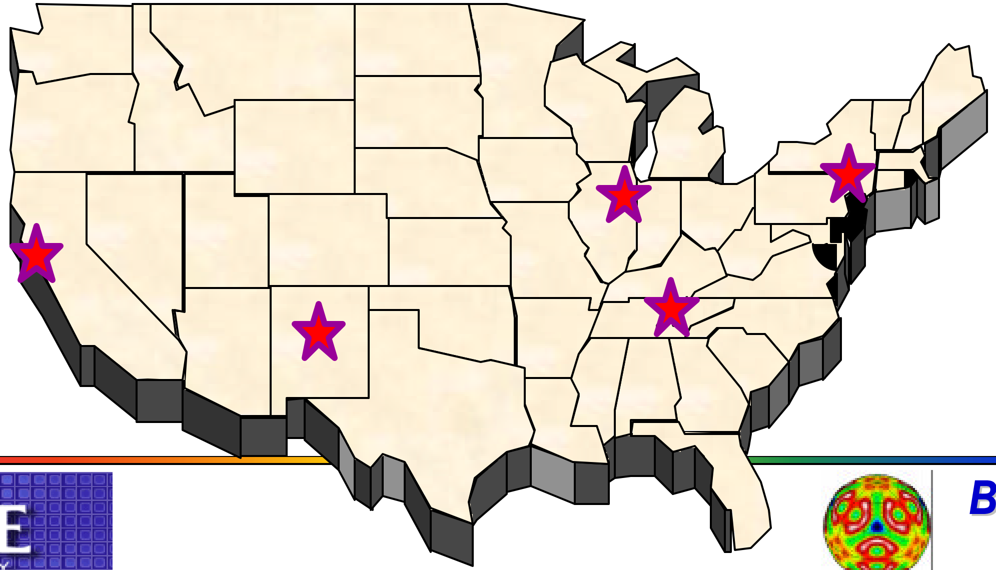
Transmission electron microscope image showing an abrupt interface and low defect density for the ferroelectric $SrTiO_3$ on Si.

The Five DOE Nanoscale Science Research Centers (NSRCs)

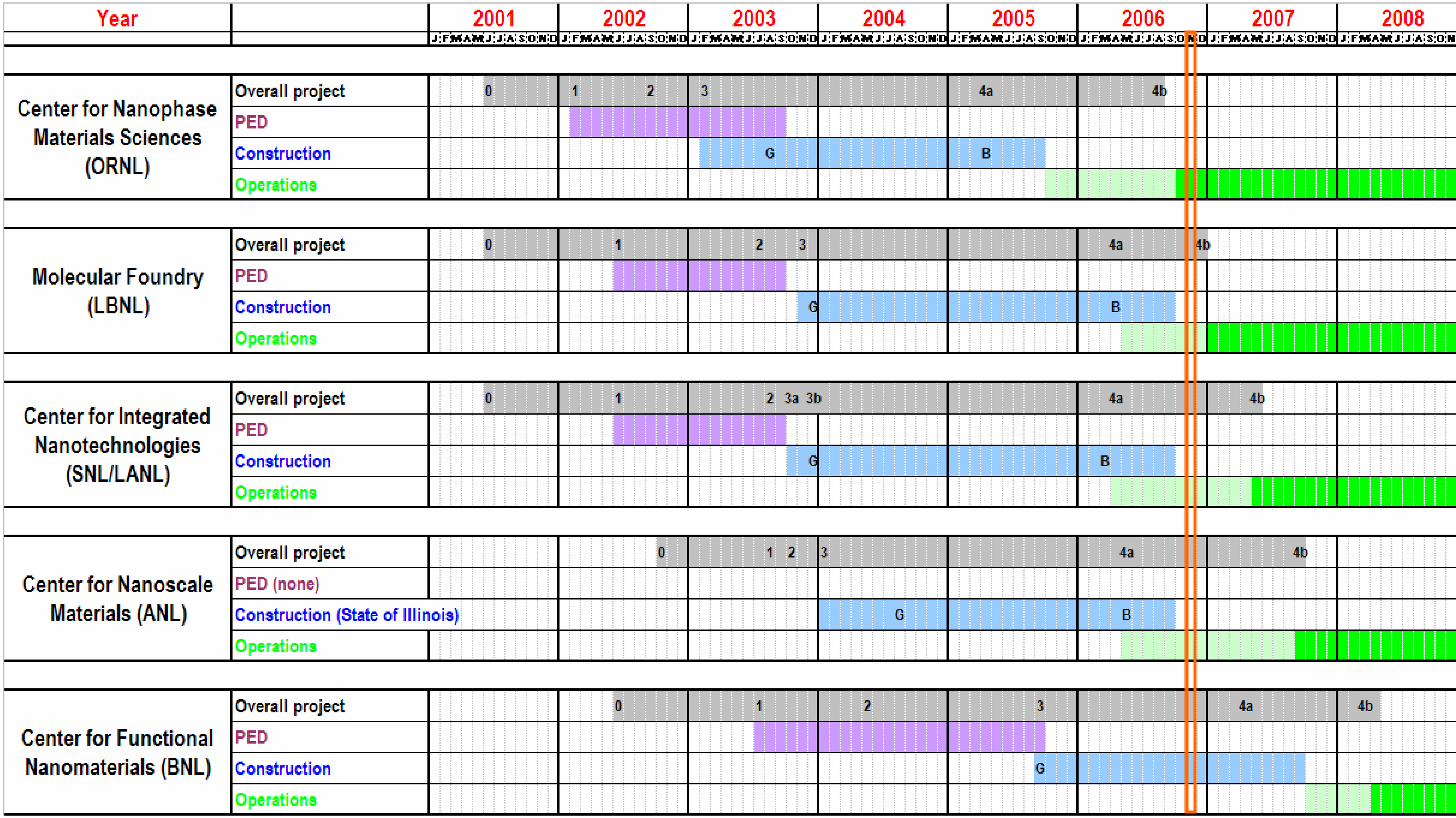


Nanoscale Science Research Centers: Basic Info

- *Research facilities for synthesis, processing, and fabrication of nanoscale materials*
- *Provide specialized equipment, unique tools, and support staff that are difficult for individual institutions to build and maintain*
- *Operated as user facilities; available to all researchers; access determined by peer review of proposals; cost recovery for proprietary work*
- *Co-located at DOE National Laboratories with existing major user facilities (synchrotron radiation light sources, neutron scattering facilities, other specialized facilities) to provide characterization and analysis capabilities*



Status of the DOE Nanoscale Science Research Centers



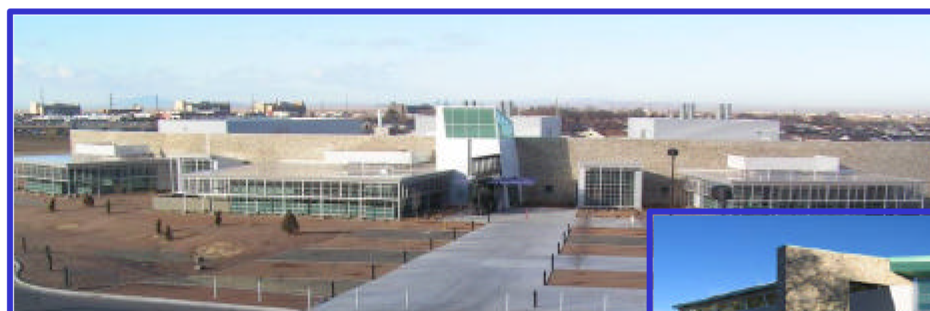
Construction is Complete and Initial Operations are Underway at Four of the Five NSRCs

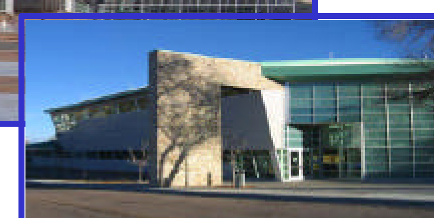
Molecular Foundry
(Lawrence Berkeley National Laboratory)

Center for Functional Nanomaterials
(Brookhaven National Laboratory)
- under construction

Center for Nanoscale Materials
(Argonne National Laboratory)

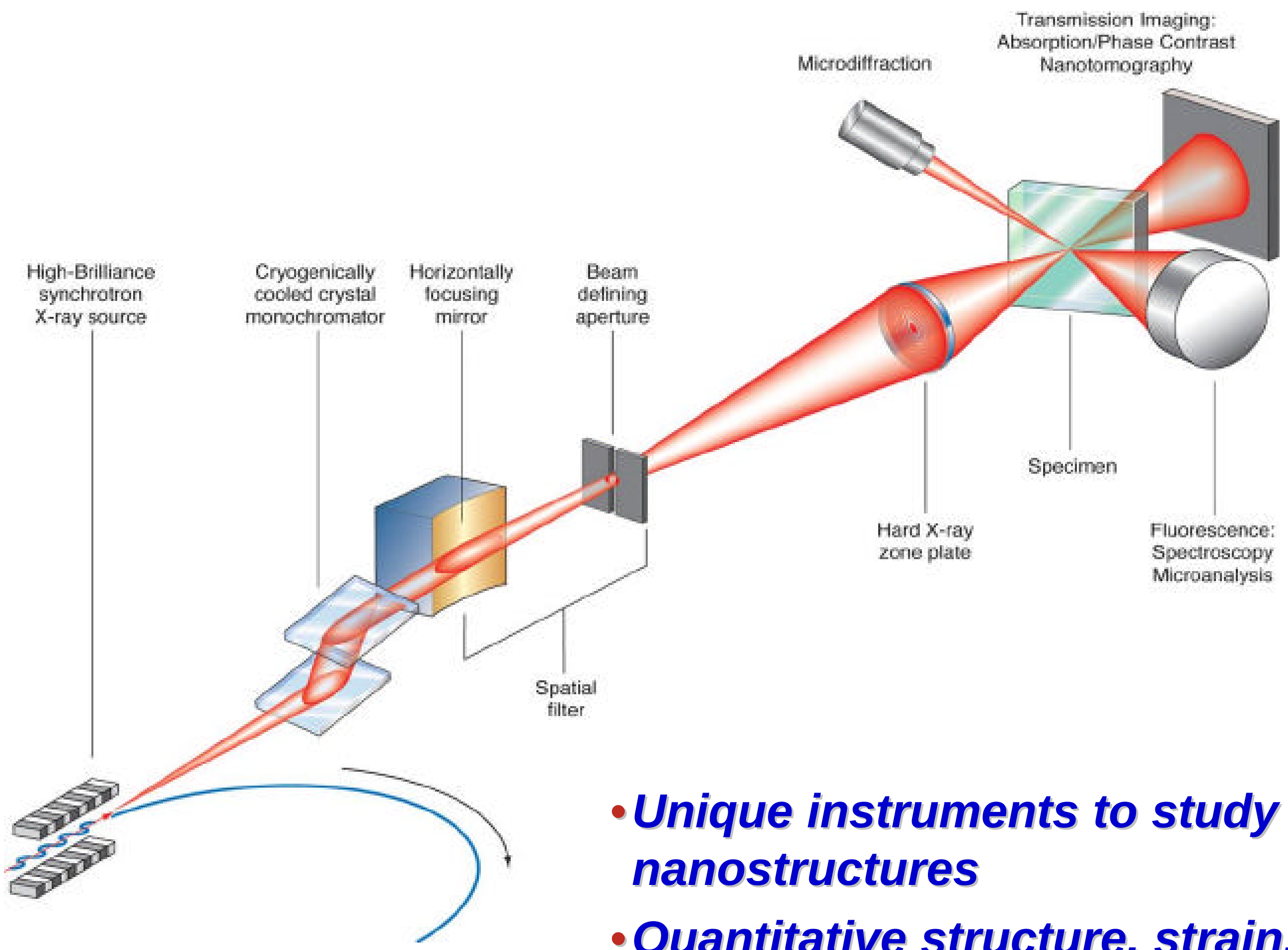
Center for Nanophase Materials Sciences
(Oak Ridge National Laboratory)





Center for Integrated Nanotechnologies
(Sandia & Los Alamos National Labs)

Unique tools: beamlines to study growth of nanostructures

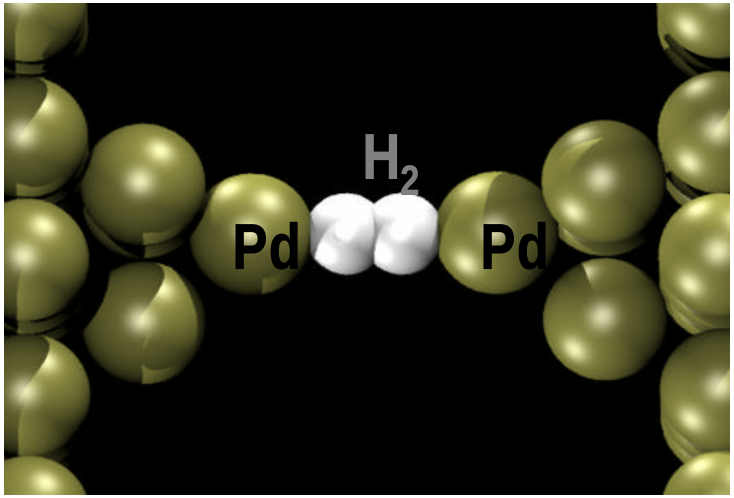


- Brookhaven
- Argonne

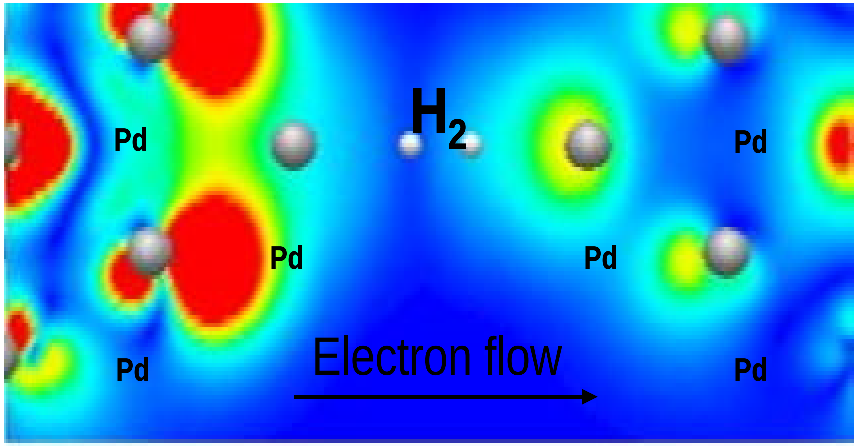
- Unique instruments to study individual nanostructures
- Quantitative structure, strain, orientation imaging
- Sensitive trace element and chemical state analysis

Calculating Resistance in the Smallest Possible Electronic Junctions

In the ultimate limit, one can imagine a junction across a single molecule. Measurements have been made in recent years on the electron transport through a single molecule of hydrogen, positioned between two metal point contacts via nanofabrication techniques. Now novel calculations have been done to understand the junction resistance. The resistance of the hydrogen molecule is extremely sensitive to the choice of contact material, a trait not seen in macroscopic junctions, and model calculations accurately reproduce these material dependences.

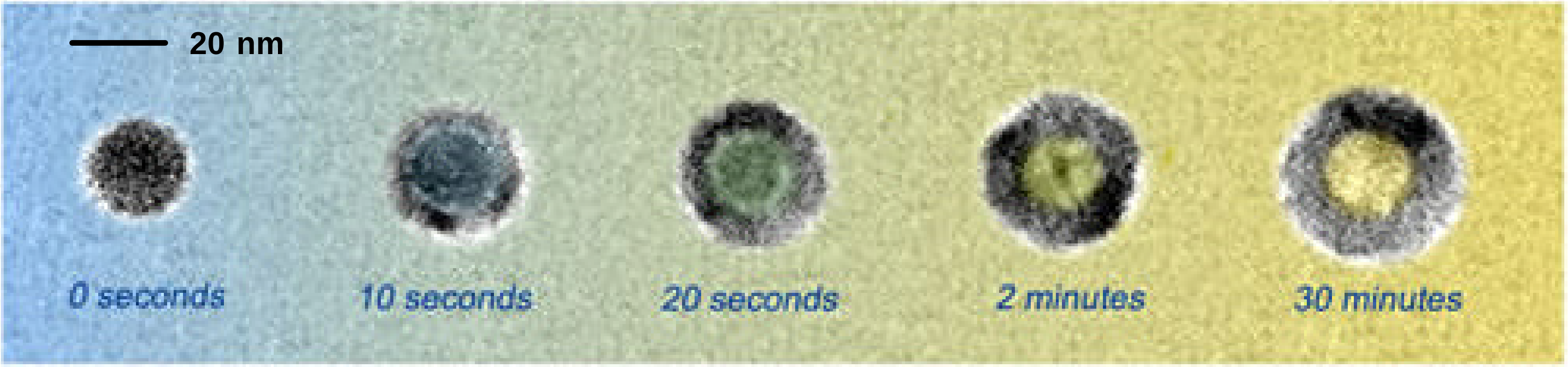


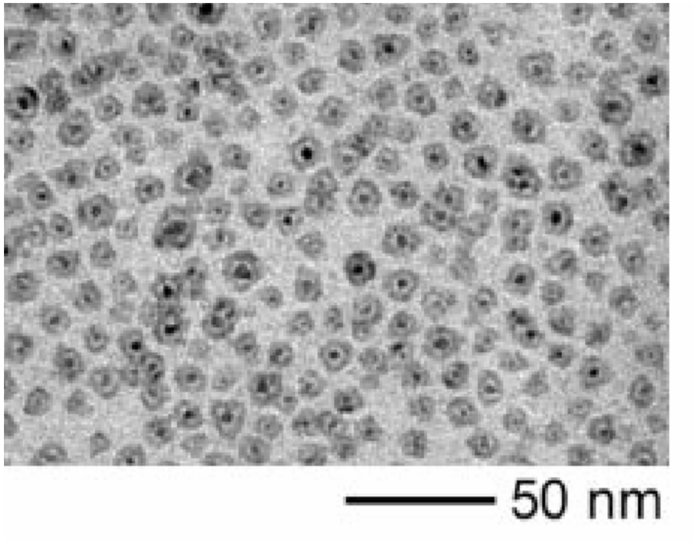
Schematic view of a single hydrogen molecule positioned between two palladium point contacts.



A density plot of the conducting electrons reveals significant build up of electron density (red) behind the tip Pd atom, leading to a high junction resistance and consistent with recent experiments.

Hollow Nanocrystals Synthesized
Catalytic Properties Measured in Nanoscale Reactors



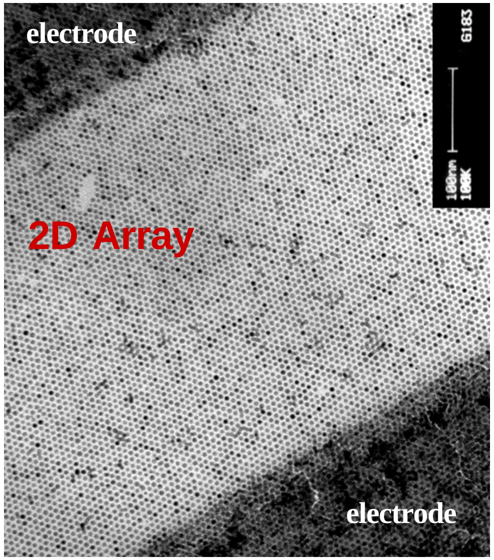


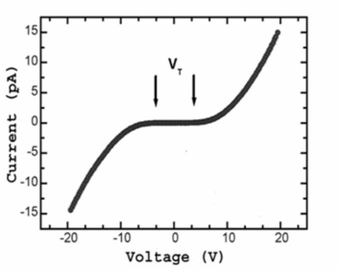
- ***Controlled synthesis of hollow nanoscale crystals (above) has been achieved via the Kirkendall effect, and has been demonstrated for a variety of metal species and their oxides. The uniformity, control, and versatility of the approach suggest a wide range of applications. For example, filling hollow cobalt oxide nanospheres with platinum (left) results in nanoscale reaction chambers that have been demonstrated to be catalytically active.***

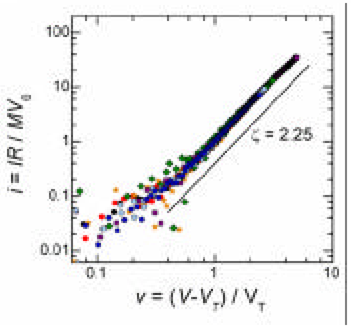
**A. P. Alivisatos and G. A. Somorjai,
Molecular Foundry**

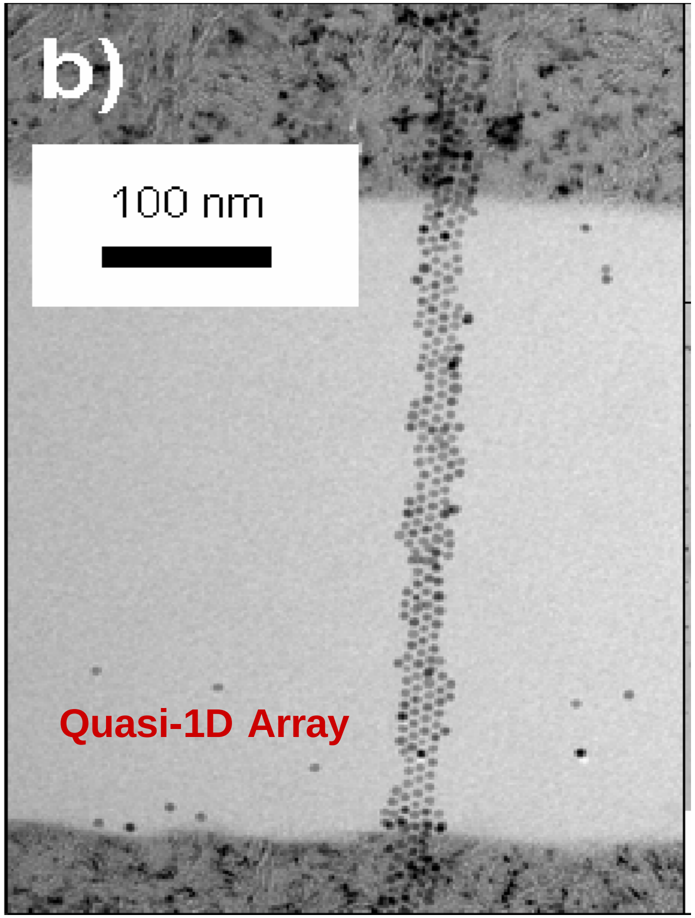
Charge Transport in Low-Dimensional Structures:
2D and Quasi-1D Nanocrystal Arrays

- ***Experiments on low-dimensional artificial solids made of nanocrystals have yielded new insights:***
  - ***I-V behavior is highly nonlinear***
  - ***Threshold voltage scales linearly with array width.***
  - ***Both structural disorder and quenched charge disorder affect tunneling***







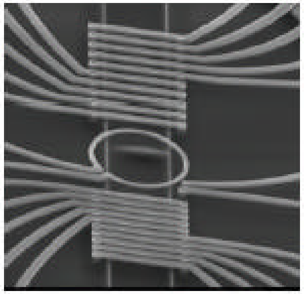


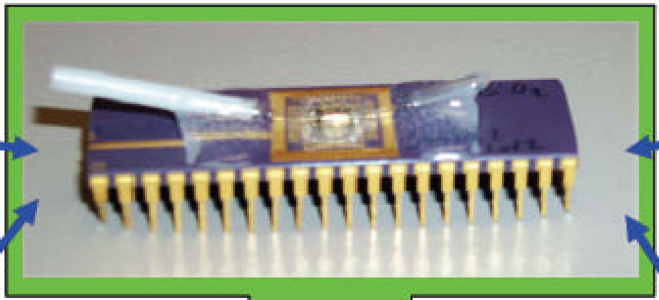
X.-M. Lin, K. Elteto, et al.,
CNM and U. Chicago

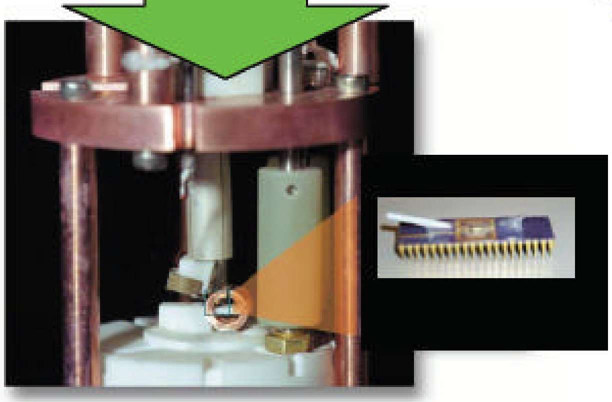
CINT Discovery Platforms™: modular micro-labs for nanoscience

Mechanics

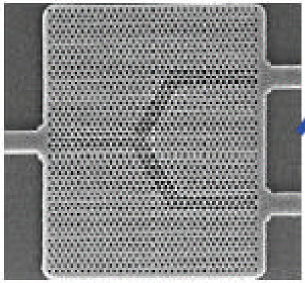
Electronics



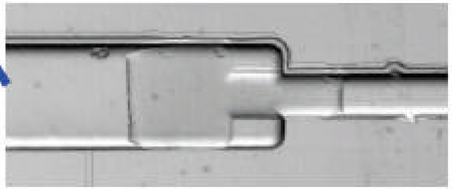




Optics



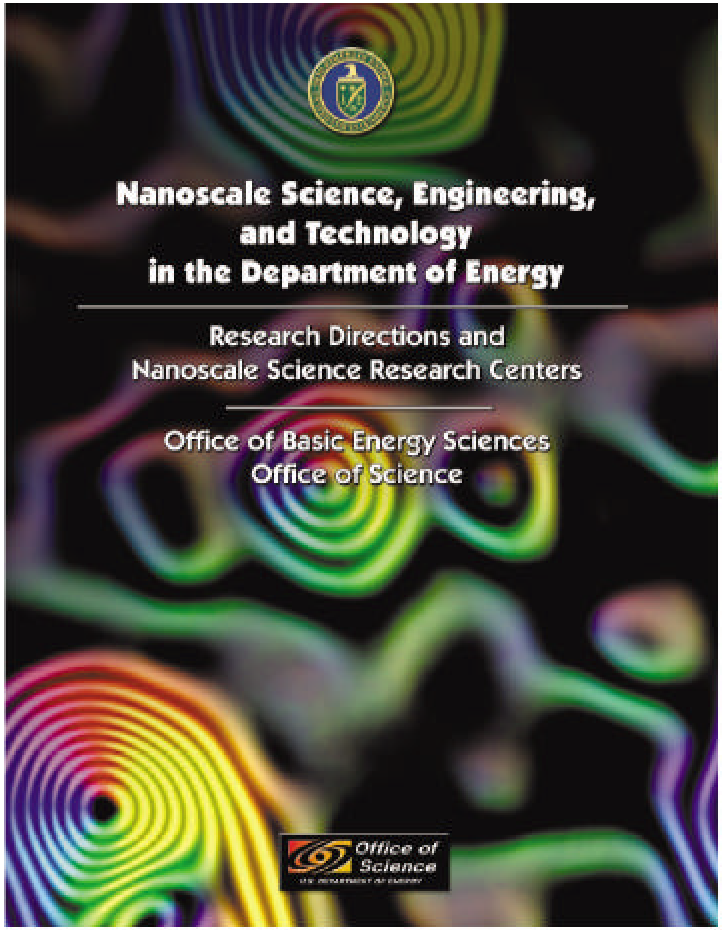
Fluidics



- Multiple in/out signals for stimulation, interrogation
- Standardized, rugged and robust
- "Pop-In" design for instrument compatibility, rapid exchange.
- Parallel architecture for statistics

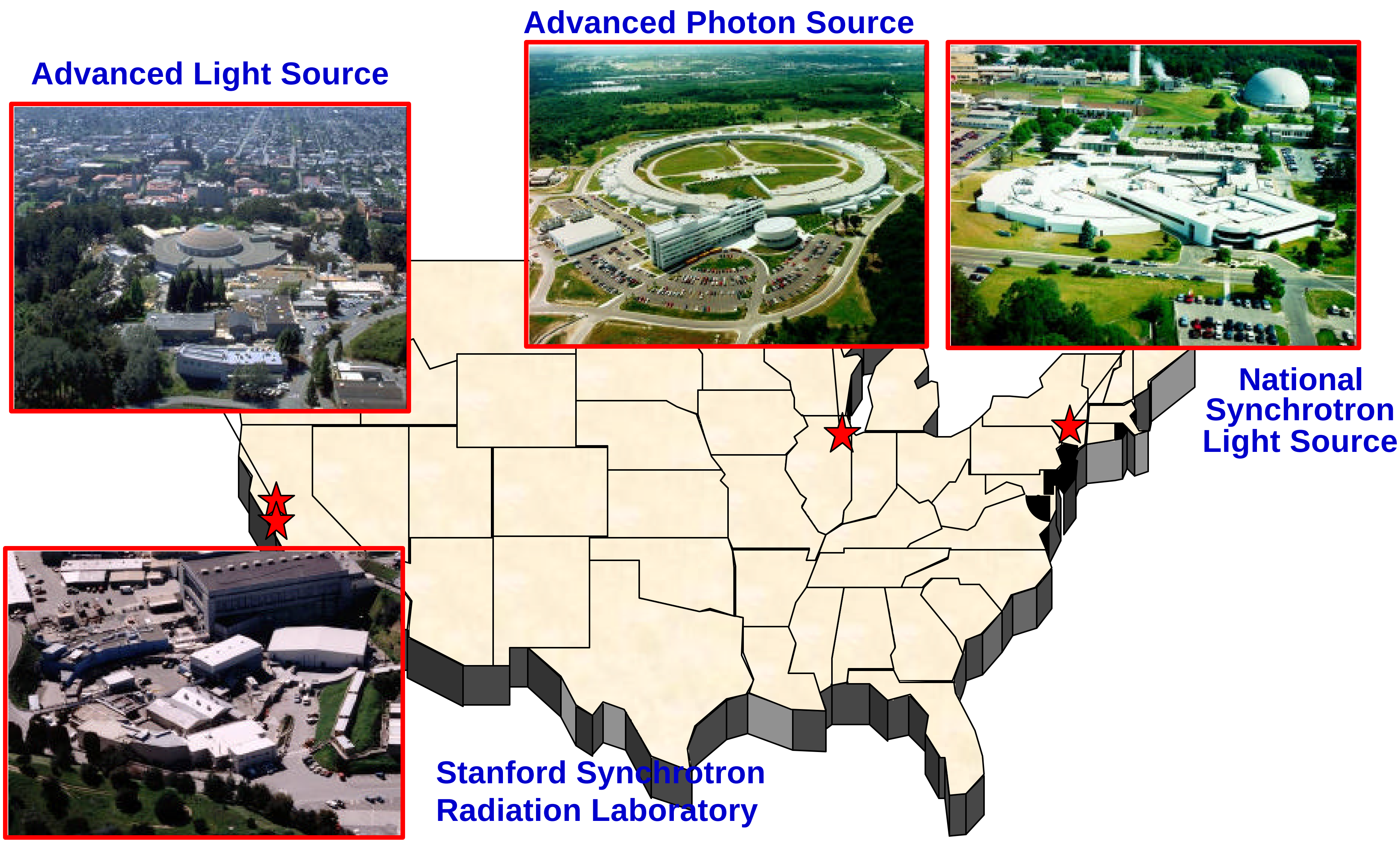
Los Alamos NATIONAL LABORATORY
Sandia National Laboratories

Further information

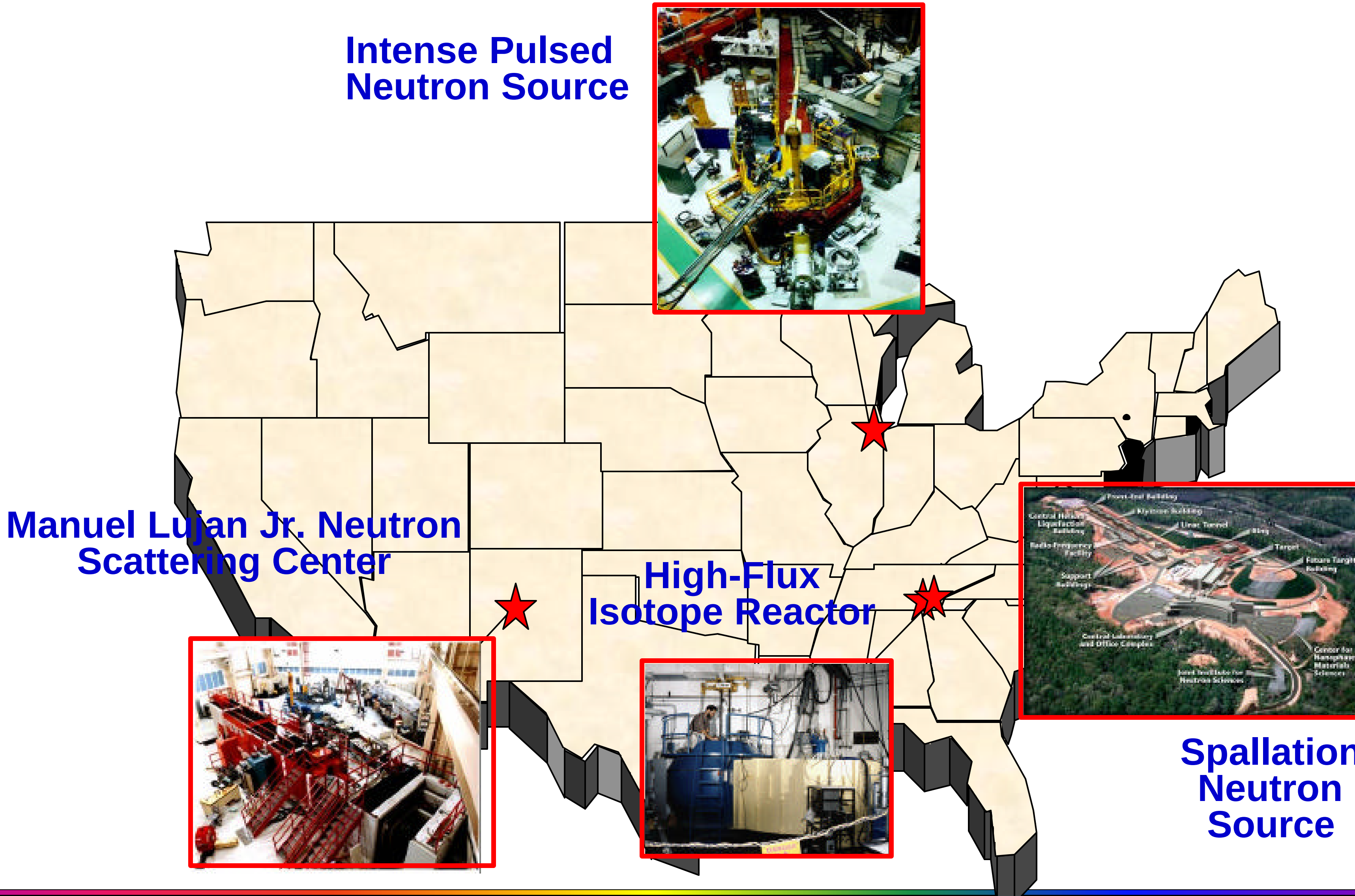


Extensive information on DOE Office of Science programs in nanoscience, including this summary brochure, is available at: http://nano.energy.gov

The DOE-BES Light Sources

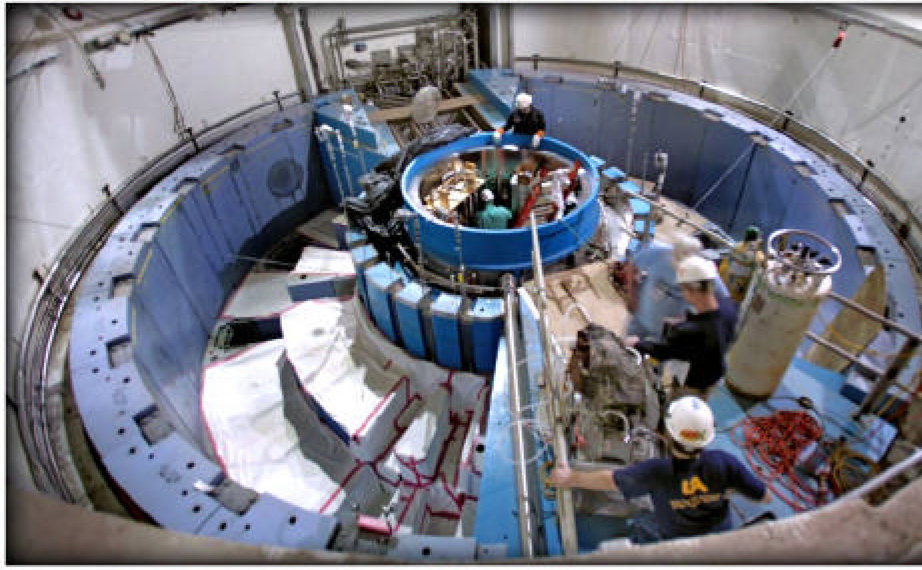


The DOE-BES Neutron Scattering Centers

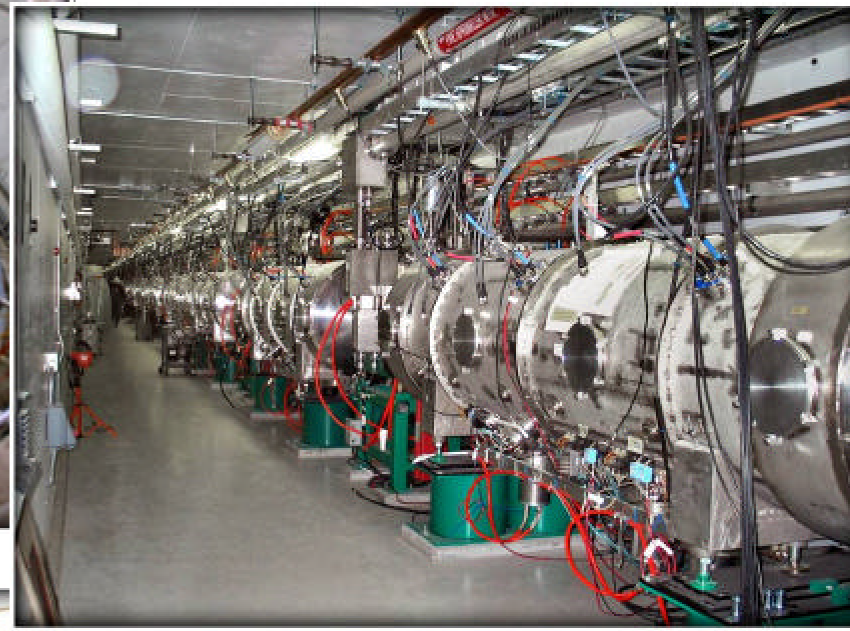


The Spallation Neutron Source

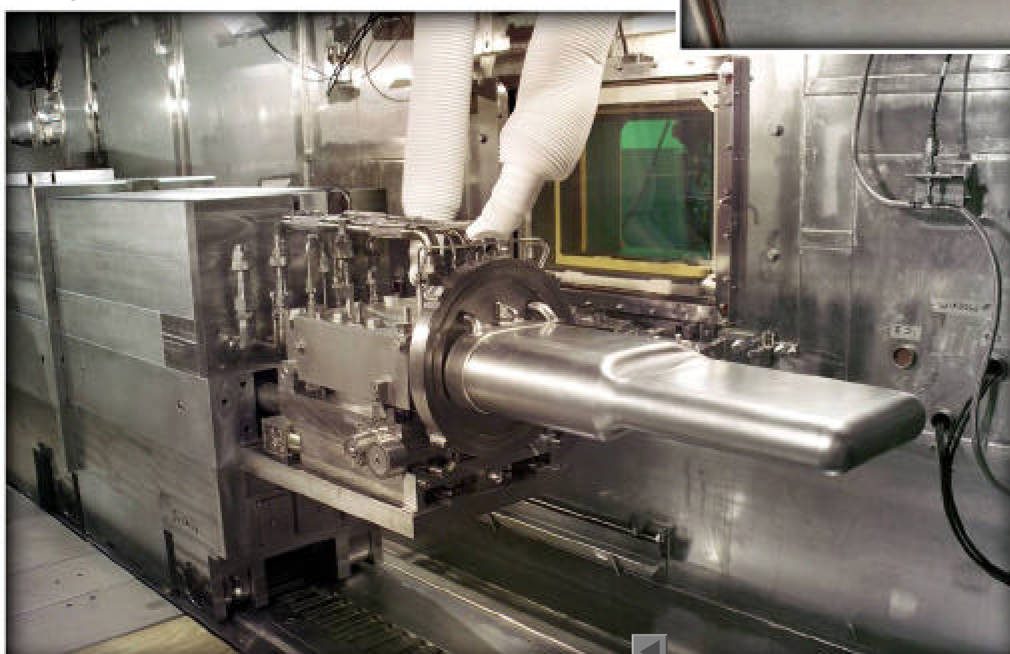
Spallation Neutron Source



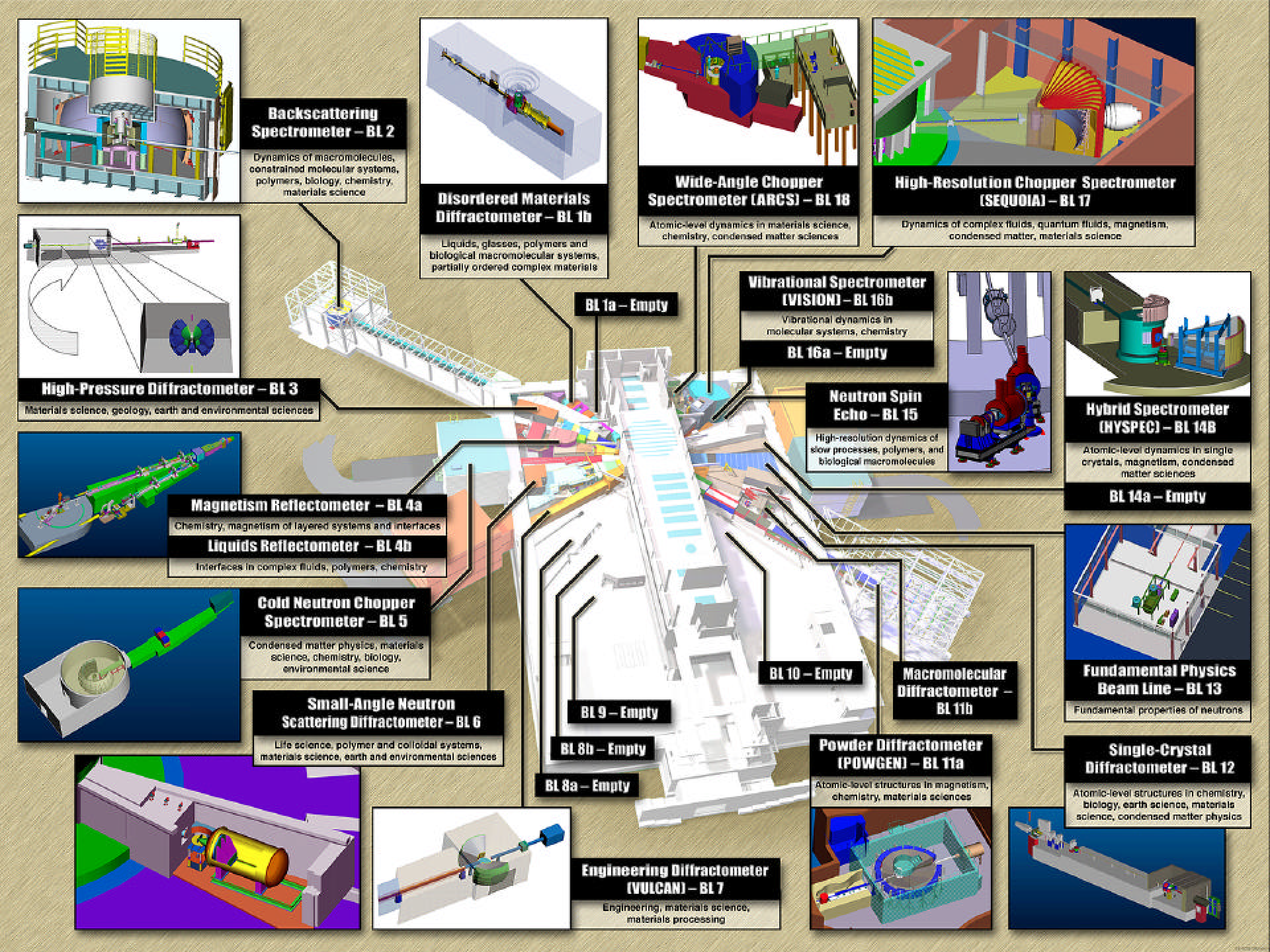
Target monolith and beam ports



Superconducting linac

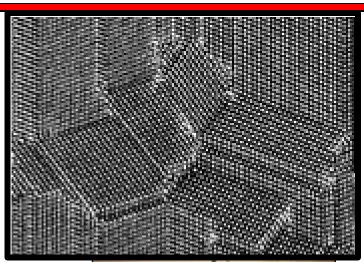


Hg target module


Backscattering Spectrometer – BL 2
Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Disordered Materials Diffractometer – BL 1b
Liquids, glasses, polymers and biological macromolecular systems, partially ordered complex materials
Wide-Angle Chopper Spectrometer (ARCS) – BL 18
Atomic-level dynamics in materials science, chemistry, condensed matter sciences
High-Resolution Chopper Spectrometer (SEQUOIA) – BL 17
Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science
BL 1a – Empty
Vibrational Spectrometer (VISION) – BL 16b
Vibrational dynamics in molecular systems, chemistry
BL 16a – Empty
High-Pressure Diffractometer – BL 3
Materials science, geology, earth and environmental sciences
Neutron Spin Echo – BL 15
High-resolution dynamics of slow processes, polymers, and biological macromolecules
Hybrid Spectrometer (HYSPEC) – BL 14B
Atomic-level dynamics in single crystals, magnetism, condensed matter sciences
BL 14a – Empty
Magnetism Reflectometer – BL 4a
Chemistry, magnetism of layered systems and interfaces
Liquids Reflectometer – BL 4b
Interfaces in complex fluids, polymers, chemistry
Cold Neutron Chopper Spectrometer – BL 5
Condensed matter physics, materials science, chemistry, biology, environmental science
Fundamental Physics Beam Line – BL 13
Fundamental properties of neutrons
BL 10 – Empty
Macromolecular Diffractometer – BL 11b
Small-Angle Neutron Scattering Diffractometer – BL 6
Life science, polymer and colloidal systems, materials science, earth and environmental sciences
BL 9 – Empty
BL 8b – Empty
BL 8a – Empty
Powder Diffractometer (POWGEN) – BL 11a
Atomic-level structures in magnetism, chemistry, materials sciences
Single-Crystal Diffractometer – BL 12
Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics
Engineering Diffractometer (VULCAN) – BL 7
Engineering, materials science, materials processing

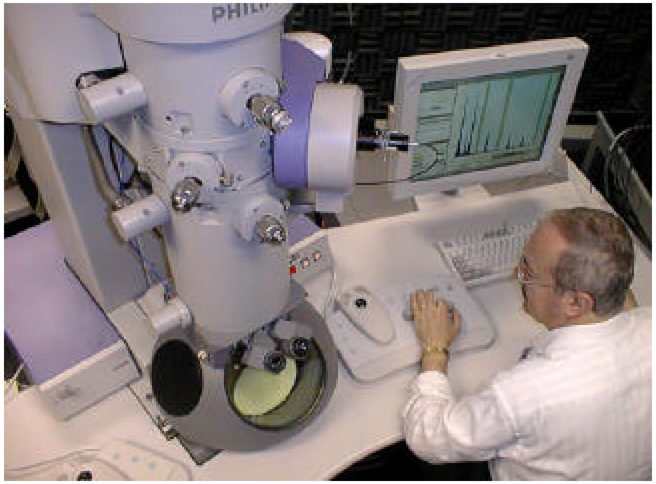
Electron Scattering User Facilities

[National Center for Electron Microscopy] (NCEM) at Lawrence Berkeley National Laboratory: atomic resolution imaging

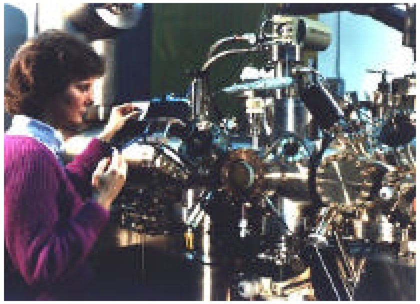


[Electron Microscopy Center] (EMC) at Argonne National Laboratory: in-situ studies, including irradiation effects

Sub-Angstrom Microscopy and Microanalysis building, under construction



[Shared Research Equipment] (SHaRE) Program at Oak Ridge National Laboratory: microanalysis and spectroscopy



Richard E. Smalley – An Energy Legacy!!!